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MATERIALS OF MACHINES.

BY

ALBERT W. SMITH,

Professor of Mechanical Engineering in
Leland Stanford Junior University, California.

FIRST EDITION.

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PREFATORY NOTE.

THIS book is a result of an effort to bring together concisely the information necessary to him who has to select materials for machine parts.

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MATERIALS OF MACHINES.

CHAPTER I.

OUTLINE OF THE METALLURGY OF IRON AND STEEL.

SECTION 1. Iron occurs in nature combined with many other substances. The world's supply of iron, however, is obtained almost exclusively from the oxides Fe_2O_3 and Fe_3O_4. Carbonate ores, $FeCO_3$, are reduced before smelting by roasting to FeO, and this FeO takes up more oxygen from the atmosphere, becoming Fe_2O_3. The formation of these oxides was accompanied by evolution of heat energy. This energy per unit weight of oxide was definite in amount and independent of the method or time of formation. To separate the oxide again into its constituents an exactly equivalent amount of energy must be supplied. In brief, the separation is accomplished

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as follows: Heat energy is supplied to the oxide whereby its temperature is raised. The bond which holds the iron and oxygen together, whatever its character, is weakened. But this alone is insufficient in this case to cause separation. Therefore the heating is caused to occur in the presence of carbon or carbon monoxide. Either of these has greater affinity for oxygen at high temperature than the iron; hence, with the help of the heat, is able to pull away the oxygen from the iron oxide, forming CO_2, which, being gaseous, passes off, leaving the iron. The heat energy supplied to weaken the bond plus the energy expended by the carbon or carbon monoxide in pulling away the oxygen from the iron is exactly equal to the heat energy that was evolved by the original combination of the oxygen and iron into iron oxide.* The real process is much more complex because of circumstances to be considered later.

Sec. 2. **Preliminary Consideration of Fuels.**—In general a fuel is a substance which will unite chemically with oxygen with the evolution of heat. Nature furnishes many such substances; as, for example, silicon, sulphur, phosphorus, manganese. These are actually used for fuel in the metallurgy of steel, as will appear later. But the fuels used ordinarily depend for their value upon the presence of hydrogen or carbon. Fuel

* By the law of Conservation of Energy.

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may be pure carbon (solid), pure hydrogen (gas), or a combination of the two, as petroleum (liquid). Fuel may therefore be a solid, a liquid, or a gas.

Solid fuels are vegetable in their origin and consist chiefly of carbon, hydrogen, and oxygen. There is also a small amount of earthy matter present, which, being incombustible, remains after combustion and is called *ash*. When hydrogen and oxygen are present in fuel in just the right proportion to form water, the hydrogen is not available for combustion, as it is already in combination with the oxygen. But any excess of hydrogen is available as fuel.

Sec. 3. **Complete Combustion** of a fuel element is its combination with that amount of oxygen which produces the most stable compound. Thus complete combustion of carbon produces CO_2, carbon dioxide; and complete combustion of hydrogen produces H_2O, water.

Complete combustion of unit weight of any fuel element invariably produces a definite quantity of heat, which is called its **calorific power.** Since this is a *quantity* of heat it is expressed in units of heat quantity; in this case **British thermal units.***

Calorific power of combustibles from experimental determinations:

* A British thermal unit is the quantity of heat necessary to raise the temperature of one pound of water through one degree Fahrenheit at the temperature of maximum density.

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Combustible.	Calorific Power.
Carbon.....	14,500 British thermal units
Hydrogen.....	62,000 " " "
Carbonic oxide....	4,320 " " "
Marsh-gas, CH_4*...	23,500 " " "

If a combustible is burned in just sufficient air for complete combustion at atmospheric pressure, the heat evolved will raise the temperature of the gases, which pass off from the furnace where combustion occurs, through a certain definite range. The temperature thus attained is called the **Calorific Intensity** of the combustible.†

Sec. 4. **Determination of the calorific intensity of carbon.** The combustion is represented thus:

$$\underset{12}{C} + \underset{32}{O_2} = \underset{44}{CO_2}$$

The molecular weights are written above the symbols. For every 12 units of carbon 32 units of oxygen must be supplied, and for every one unit of carbon 32/12 units of oxygen must be supplied. But the oxygen is

* Since one pound of marsh-gas is composed of 12 oz. of carbon and 4 oz. of hydrogen, it would seem that its calorific power should be 12/16 of 14,500 + 4/16 of 62,000 = 10,875 + 15,500 = 26,375 instead of 23,500. The difference, 2,875, is the energy used in separating the hydrogen from the carbon of the marsh-gas.

† The temperature is raised through a certain *range*, and hence the final temperature attained will depend upon the temperature of the air which supplies oxygen for combustion. Hence this temperature must be added to the range due to heating to get the final temperature.

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supplied from the atmospheric air; and this is composed by weight of nitrogen, 0.77, oxygen, 0.23. Hence for every 23 parts of oxygen supplied 100 parts of air must be supplied, and for every one part of oxygen 100/23 parts of air must be supplied. Therefore, for the complete combustion of one pound of pure carbon the amount of air to be supplied equals $32/12 \times 100/23 = 11.6$ lbs. The gases which pass off when the combustion of carbon is perfect are nitrogen and carbon dioxide. The nitrogen is inert as far as combustion is concerned. Its amount equals 77% of the air supplied, that is, $11.6 \times 0.77 = 8.93$ lbs. For every pound of carbon $44/12 = 3.66$ lbs. of CO_2 are produced.

The heat evolved by the combustion of one pound of carbon is 14,500 B.T.U. This quantity of heat is available to raise the temperature of 8.93 lbs. of nitrogen and 3.66 lbs. of CO_2, and the resulting increase in temperature, t, is required. The specific heat of nitrogen equals 0.244, and of CO_2 equals 0.2164, and hence for every degree that 8.93 lbs. of nitrogen is heated there are used 8.93×0.244 B.T.U., and to heat it to the temperature t, $8.93 \times 0.244 \times t$ B.T.U. are used. Similarly, to heat 3.66 lbs. CO_2 to t, $3.66 \times 0.2164 \times t$ B.T.U. are used. But the amount of heat that raised the temperature of both to t is 14,500 B.T.U. Therefore $t(8.93 \times 0.244 + 3.66 \times 0.2164) = 14,500$; hence

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$t = 4872°$ F., the increase in temperature. Assuming that the temperature of the air supporting combustion was 65° before combustion began, the calorific intensity equals $4872° + 65° = 4937°$ F.*

Sec. 5. **Determination of the calorific intensity of carbonic oxide.** The combustion is represented thus:

$$\begin{matrix} 28 & 16 & 44 \\ CO + O = & & CO_2 \end{matrix}$$

Therefore, for every 28 parts of CO 16 parts of oxygen must be supplied, or for one part of CO 16/28 parts of oxygen must be supplied, and for every part of oxygen 100/23 parts of air are required. Therefore, for every pound of CO $16/28 \times 100/23 =$ 2.48 lbs. of air are required. Of this air $0.77 =$ nitrogen $= 1.9$ lbs. Also the CO_2 produced equals $44/28 = 1.57$ lbs. The weight of nitrogen heated therefore equals 1.9 lbs., and of CO_2 equals 1.57 lbs. To raise the temperature of these gases 4320 B.T.U. are available. Hence

$$t = \frac{4320}{(1.9 \times 0.244) + (1.57 \times 0.2164)} = \frac{4320}{.803} = 5380° \text{ F.},$$

= the increase in temperature. Adding 65° as before gives the calorific intensity = 5345° F. In the case of carbon burned to CO_2, 14,500 B.T.U. were avail-

* Obviously the slight variations in temperature of the air supporting combustion have but little effect upon the calorific intensity.

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able to raise the temperature of 8.93 lbs. nitrogen and 3.66 lbs. CO_2. The reason for the higher calorific intensity of CO is, therefore, that while the available heat is less, the weight of gases to be heated is less in greater degree.

Sec. 6. **Determination of the calorific intensity of hydrogen.** The combustion is represented thus:

$$\begin{matrix} 2 & 16 & 18 \\ 2H & + O & = H_2O \end{matrix}$$

For every part of hydrogen 8 parts of oxygen must be supplied. The corresponding amount of air = 100/23 × 8 = 34.8. Hence the combustion of one lb. of hydrogen requires 34.8 lbs. of air. Of this 0.77 = nitrogen = 26.8 lbs. The water resulting from the combustion = 18/2 = 9 lbs. This water not only has its temperature raised, but it is converted into steam, and this steam is superheated. Supposing the conversion into steam to occur at atmospheric pressure, the heat required is 966 B.T.U. per pound of water. This heat has no effect upon the temperature, hence it may be subtracted from the calorific power of hydrogen, leaving the heat available for raising the temperature =

$$62{,}000 - (9 \times 966) = 53{,}306.$$

This heat is applied (first) to raise the temperature of the water from the temperature, t_1, of the air-supply

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before combustion, to the temperature of vaporization, 212° F.; (second) to superheat the steam formed to the temperature t; (third) to raise the temperature of the nitrogen from t_1 to t. The specific heat of water is 1.0, of steam is 0.48, of nitrogen is 0.244. Hence

$$(212 - t_1)9 + (t - 212)(9 \times 0.48) + (t - t_1)(26.8 \times 0.244) = 53,306.$$

Whence,

$$\text{if } t_1 = 65° \text{ F.}, \quad t = 4910° \text{ F.}$$

Hence, although the calorific power of hydrogen is far greater than that of carbon, its calorific intensity is about the same. The reasons for this are the greater relative weights of the substances heated, their greater capacity for heat, and the absorption of heat for the vaporization of water with no resulting change of temperature.

The theoretical temperatures thus found are never attained, because (*a*) combustion is seldom complete; (*b*) an excess of air is always supplied; (*c*) the fuel is seldom entirely consumed; (*d*) there are always radiation losses; (*e*) the moisture usually present in the fuel absorbs heat in being vaporized and heated; and (*f*) at high temperature the tendency of carbon and hydrogen to combine with oxygen is changed into a tendency to dissociate with absorption of heat and reduction of temperature. See Sec. 15.

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Sec. 7. **Solid Fuels** may be classified as:

(*a*) Raw Fuels, such as coal and wood.

(*b*) Artificial Fuels, such as coke and charcoal.

Raw Fuels. **Coal** is often classified as follows:

Coal { Lignite. / Bituminous coal. / Anthracite coal.

Vegetable matter is really converted into coal by gradual change; hence each division of the classification covers a wide range and blends into the others. Description of coals is unnecessary here.

The following table of percentage compositions shows the chemical changes which occur while woody fibre is changed to anthracite coal:

	Carbon.	H. & O. in proportion to form water.	H. available for Combustion.
Wood.....	48.5	50.9	0.6
Peat.....	59.4	39.0	1.6
Lignite.....	65.0	33.0	2.0
Bituminous coal..	78.0	19.0	2.8
Anthracite coal..	94.0	4.0	2.4

During this change the percentage of available combustible increases, and the percentage of water to absorb heat decreases; hence the calorific intensity increases.

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Sec. 8. **Wood.**—According to Professor Thorpe,* woody tissue when freed from soluble and other foreign matter has a percentage composition as follows: Carbon, 48.5; hydrogen, 6.2; oxygen, 45.3. Since eight parts by weight of oxygen unite in combustion with one part of hydrogen, it follows that if the percentage of hydrogen present were $45.3 \div 8 = 5.6+$, the oxygen and hydrogen would be present in just the right proportion to form water, and no hydrogen would be available for the evolution of heat. The amount of hydrogen really present is 6.2%; hence only the difference, $6.2 - 5.6 = 0.6\%$ of hydrogen is available. This is practically negligible. Only 48% of pure woody tissue is available for fuel. The calorific intensity is therefore low for this reason and also because the water resulting from the breaking up of the woody tissue, and that present as moisture, must be vaporized with absorption of heat unaccompanied by rise in temperature. Therefore wood cannot be used directly as a fuel for the production of very high temperatures.

Sec. 9. **Artificial Fuels. Coke.**—Bituminous coal, as shown in the foregoing table, contains carbon, hydrogen, and oxygen. There is also a small amount of nitrogen present.

If this coal be highly heated in a closed retort, it will

* Coal: its History and Uses, pp. 164–5. Edited by Professor Thorpe. Published by Macmillan & Co.

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not burn because of the exclusion of oxygen, but destructive distillation will take place. The products of this process may vary with the time occupied, the temperature, the quality of the coal, and other conditions, but in general are as follows:

(*a*) Combinations of hydrogen and carbon in a very wide range of proportions, resulting in solid, liquid, and gaseous hydrocarbons.

(*b*) Combination of hydrogen and nitrogen into ammonia.

(*c*) Combinations of hydrogen, nitrogen, and carbon into aniline and many other compounds.

(*d*) Combinations of carbon, hydrogen, and oxygen into phenol and other compounds.

(*e*) Combinations of carbon and oxygen into carbon monoxide and carbon dioxide.

(*f*) Pure hydrogen.

(*g*) A nearly pure residue of carbon which is called *coke*.

When sulphur is present, sulphur dioxide and other compounds of sulphur and the other elements present are produced.

Sec. 10. **Charcoal.**—Wood may also be subjected to destructive distillation, the process being essentially the same as that just described. The carbon residue is called charcoal.

The object of the processes for the production of coke and charcoal is to produce a concentrated fuel by

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removing all substances except the available fuel element carbon. Obviously this increases the temperature produced by combustion, i.e., the calorific intensity.

Gaseous hydrocarbons, carbon monoxide, and hydrogen are gas fuels which pass off, and hence, unless these are utilized, the process sacrifices a portion of the fuel in order to gain in calorific intensity.

Sec. 11. **Gas Fuel** has several advantages over solid fuel for many metallurgical processes.

1. Inferior solid fuel may be used for the generation of the gas fuel.

2. The furnace for the production of the gas may be at a distance from the furnace where the gas is used, the transfer being made through pipes. Valuable space is thereby sometimes saved.

3. Heat may be more easily applied uniformly over a given surface, or concentrated locally, with gas fuel than with solid fuel.

4. The air which supports combustion can be much more completely mixed with the fuel, and therefore the excess of air over that necessary for complete combustion is reduced to a minimum, with a resulting gain in calorific intensity.

5. If the mixture of air and gas be properly regulated, there will be a complete absence of smoke and soot, and the latter will not be mixed with the material treated.

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Sec. 12. **Production of Gas Fuel.**—There are three processes for the production of gas fuel from solid fuel: Illuminating-gas process, water-gas process, and producer-gas process.

Illuminating-gas Process.—Destructive distillation of coal containing a large percentage of volatile constituents. This process is similar to that for the production of coke, gas being the product and coke a by-product. The gas produced is illuminating-gas. Its composition is variable, but usually about as follows:

H,	40 to 50%	by volume.
CH_4,	30 to 40%	" "
CO,	8 to 14%	" "

There are usually also small amounts of C_2H_4, nitrogen, oxygen, CO_2, and vapor of water.

Sec. 13. **Water-gas Process.**—Another method is to pass steam over incandescent carbon. The product is known as "water-gas." The reactions are as follows:

$$C + 2H_2O = CO_2 + 4H.$$
$$CO_2 + C = 2CO.$$
$$CO + H_2O = CO_2 + 2H.$$

These reactions probably go on simultaneously, and when the process is properly regulated the gas has about the following composition:

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CO_2,	2 to 15%	by volume.
CO,	20 to 40%	" "
H,	50 to 65%	" "
CH_4,	4 to 8%	" "
C_2H_4, etc.,	0 to 6%	" "

When this gas is used for illumination it is passed through a second furnace, where it takes up vaporized hydrocarbons.

Sec. 14. **Producer-gas Process.**—This process, the most important to the metallurgist, consists of burning coal with incomplete air-supply.

Fig. 1 shows a form of gas-producer. It consists of a chamber, *A*, lined with fire-brick, and having suitable grate at the bottom. Bituminous coal is introduced through a hopper, *B*, so arranged that communication with the air need not be made when the solid fuel is put in. Air is admitted through the grate, and at *D* there is a steam-blower used to force combustion and to introduce steam. The chamber is connected to the gas-flue by the passage *C*. The most rapid combustion occurs near the grate. The action is as follows: Air passes through the grate and combines with the incandescent carbon, forming CO_2. This passes up and comes in contact with more incandescent carbon where the oxygen supply is small, and takes up more carbon and becomes CO, passing up into the chamber. In the upper part of the coal, where the

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heat is less intense, the volatile constituents distil off; in fact, the action is the same as in the illuminating-gas retorts, with the production of hydrogen, hydrocarbons, carbon monoxide, etc.

This, of course, leaves coke, which descends slowly,

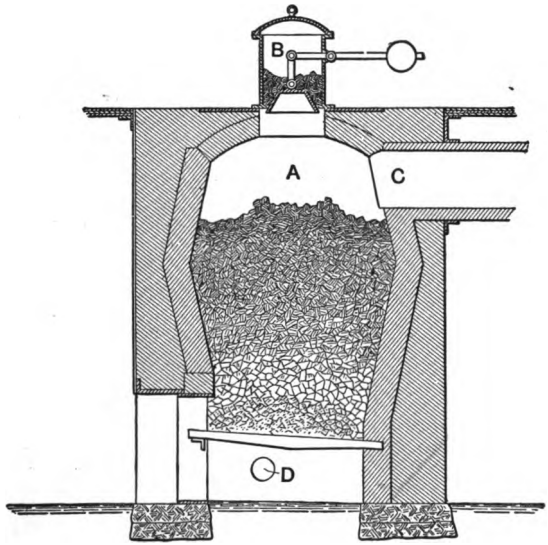

FIG. 1.

becoming incandescent, and uniting with the oxygen and CO_2 to form CO. Also the steam from the blower passes through the grates with just the same result as in the manufacture of water-gas, viz., the production of hydrogen and carbon monoxide. Steam has an advantage over air, in that it carries no inert nitrogen to absorb heat, but it has the disadvantage of high capacity for absorbing heat, and if it be admitted in

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too large quantities it reduces the temperature in the furnace.

An average of the resulting gases from this process is as follows:

Combustible	CO,	24.2%	by volume.
	H,	8.2%	" "
	CH_4	2.2%	" "
Incombustible	CO_2,	4.2%	" "
	N,	61.2%	" "

Sec. 15. Therefore 34.6% of this gas is combustible, while 65.4% is incombustible, and hence it must be a fuel of low calorific intensity. It would seem, therefore, that "producer gas" could not be used for producing high temperatures. It becomes available for this purpose, however, through the **Siemens Regenerative Furnace,** the invention of Messrs. Frederick and C. W. Siemens. The gas, instead of being admitted to the furnace directly, passes through a chamber, *B* (Fig. 2), filled with "chequer work," i.e., full of small intricate passages, surrounded by refractory material suitable for absorption of heat. The air also passes through a similar chamber, *A*, and meets the gas at *C*, the entrance to the hearth *D*, where the metal is treated. The air is admitted above the gas, so that, because of its greater specific gravity, it shall mix more completely with the gas. Combustion occurs at *C*, and the products of the combustion, heated to a

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temperature corresponding to the calorific intensity of the fuel, pass over the hearth and through the chambers A_1 and B_1 to the stack. In passing they heat up these chambers to their own temperature, if the process is sufficiently long continued. Then the connections are changed so that the gas comes in through B_1, and

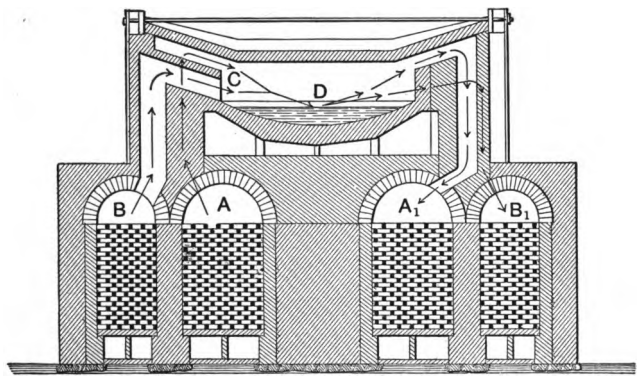

FIG. 2.

the air-supply through A_1, and A and B are connected with the stack. The gas and air passing through the heated chambers have their temperature raised before combustion takes place; then the temperature is still further raised by the combustion, so that the products of combustion now pass to the stack through A and B until the temperature of these chambers is raised to this higher temperature. Then the connections are again reversed and the entering gas and air are heated to this higher temperature before combustion, and so on. It

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would seem that an indefinitely high temperature could be produced in this way, but a limit is set at about 4000° F. The reason is as follows: Carbon is slowly oxidized at atmospheric temperatures. As the temperature is raised the tendency for carbon and oxygen to combine becomes stronger. The strength of this tendency increases with the temperature, but reaches a maximum, and then decreases with increasing temperature. Finally the tendency becomes zero, and further increase in temperature results in the *dissociation* of CO or CO_2, with corresponding absorption of heat. The temperature varies in different parts of a furnace using solid or gas fuel, and when the average temperature is high (say 2500° or 3000° F.), probably both combination and dissociation of carbon and oxygen, or of carbonic oxide and oxygen, occur simultaneously; the combination evolving heat and the dissociation absorbing heat. If the evolution of heat exceed the absorption, the average temperature will rise; but if the absorption exceed the evolution, the average temperature will fall. Suppose that the conditions are such in a furnace that combination exceeds dissociation, it follows that the temperature will rise; but in rising it approaches that temperature at which combination and dissociation are equal. At this temperature there is no increase of heat, and therefore no tendency to raise the temperature; hence it is the highest temperature that can be attained. The steam

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which results from the combustion of hydrogen may be broken up again into hydrogen and oxygen if the temperature be sufficiently raised.

From this it follows that in a Siemens regenerative furnace using fuel composed of carbon and hydrogen, the temperature that can be produced is limited. Experience shows that this limit, under ordinary conditions, is probably about 4000° F.

Sec. 16. **Refractory Materials.** — Furnaces and receptacles for metallurgical work require to be lined with material that is capable of withstanding high temperatures, i.e., refractory material.

Fire-clay is a hydrated silicate of alumina with excess of silica and with small and varying percentages of lime, magnesia, and oxide of iron. Because of the presence of water of hydration fire-clay has the quality of mixing mechanically with water and becoming plastic. It may then be moulded into any required form, the mechanically mixed water may be removed by drying and the water of hydration may be removed by "burning" or calcining. A hard, strong, and very refractory material—anhydrous aluminum silicate—results from this process. The tendency to shrinkage, distortion, and cracking during burning is partially neutralized by mixing coke-dust, graphite, or silica sand with the plastic clay.

Ganister is fire-clay with very great excess of silica. It is changed in volume only slightly by burning, and

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hence it may be formed while plastic into the furnace itself and burned in place.

Fire-clay is *acid*, and when a *basic* furnace-lining is required **Dolomite**—Magnesian limestone—is used. It consists of carbonates of magnesia and lime from which the carbon dioxide is driven off by calcining. The resulting mixture of magnesia and lime has little coherence and hence it is coarsely ground and mixed with tar into a plastic material, which is formed into the furnace-lining. Heating then cokes the tar and it becomes a cement for the magnesia and lime.

Sec. 17. **Sources of Iron.**—Full consideration of the ores of iron is beyond the scope of this work.*

Iron ores may be classified as follows:

1. Magnetic oxide, or Magnetite, Fe_3O_4.
2. Ferric oxide, or Red Hæmatite, Fe_2O_3.
3. Hydrated ferric oxide, or Brown Hæmatite, Limonite, Bog ores, etc.
4. Ferrous carbonate or Spathic ore, $FeCO_3$.

These ores always carry other substances, and the proportions vary between wide limits. The following table † gives some idea of these proportions.

Magnetic oxide, Fe_3O_4, may be regarded as a compound of ferrous oxide, FeO, and ferric oxide, Fe_2O_3.

* Ore Deposits of the United States, J. F. Kemp ; Scientific Publishing Company. Iron (The Metallurgy of), T. Turner; J. B. Lippincott Company.

† Condensed from a table given by T. Turner in Iron (The Metallurgy of).

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	Magnetite, Swedish.	Red Hæmatite, Cumberland.	Brown Hæmatite, Northampton.	Carbonate, Staffordshire Clay Ironstone.
Ferric oxide (Fe_2O_3)	65	90	65	0.5
Ferrous oxide (FeO)	25	.....	.....	47
Manganous oxide (MnO)	.....	.....	0.5	2
Carbon dioxide (CO_2)	.....	.....	.....	30
Silica (SiO_2)	10	6	13	10
Alumina (Al_2O_3)	.....	1	3	5
Lime (CaO)	.....	1	.....	2
Magnesia (MgO)	.....	.....	.....	2
Phosphoric anhydride (P_2O_5)	0.03	0.04	1.3	0.04
Water	.....	.....	14	1

The ore may also contain sulphur and arsenic. These, with the carbon dioxide and water, may be removed as vapor or gas, at comparatively low temperatures, by the process of calcining or roasting.

Sec. 18. For **Calcining** or **Roasting** the ore is piled in heaps out of doors, or charged into kilns, with fuel in proper amount mixed with it. The fuel is ignited, the mass is slowly heated up. Water is driven off as steam. If the ore is carbonate, $FeCO_3$, the CO_2 is driven off, and the resulting FeO is changed to Fe_2O_3 by combination with oxygen of the air. If any iron pyrites, FeS_2, is present the sulphur is oxidized, passing off as SO_2, while the iron is also oxidized, remaining as Fe_2O_3. Arsenic is oxidized and vaporized if present. By the process of roasting the structure of the ore is made more open, and hence better fitted for smelting.

When roasting is carried on in kilns it is often a

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continuous process. The kiln is like a foundry cupola, much enlarged in diameter. The ore and fuel are charged in at the top, and the roasted ore is withdrawn from openings at the bottom.

The process is now usually omitted for oxide ores, the roasting being accomplished in the top of the blast-furnace stack.

Sec. 19. The **early methods** for the production of iron were *direct methods*, i.e., the product was *wrought iron*, which had not passed through the intermediate state of *cast iron*.

Chemically these methods are as follows: Rich ore, Fe_2O_3, or Fe_3O_4, is charged with charcoal into a rectangular hearth, and air-blast is supplied. The coal is ignited and the oxygen of the air combines with the carbon of the fuel to form CO_2, which passing on over more incandescent carbon is reduced to CO, which comes in contact with the Fe_2O_3, when the following reactions take place:

$$3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2$$
$$2Fe_3O_4 + 2CO = 6FeO + 2CO_2$$
$$6FeO + 6CO = 3Fe_2 + 6CO_2.$$

Metallic iron and CO_2 are therefore produced. But the ore also contains some silica, alumina, etc., which are very infusible, and which must be rendered fluid for removal from the iron. It happens that silica and alumina unite with FeO to form a double alumino-

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ferrous silicate or *slag*, which is fusible at a low temperature. Some of the FeO which is produced during the process (see above reactions) acts as a "*flux*," i.e., renders the earthy matter fluid, separating it as fluid slag, which may be partly drawn off, while the iron remains in the hearth a spongy mass filled with molten slag. The mass is heated to a welding temperature and taken to a hammer or squeezer, where the slag is removed by impact or pressure, and the mass is welded into a *bloom*.

The details of the carrying out of this process vary. It requires rich ore, charcoal for fuel, and the waste of iron in the slag is very great. It is a very expensive process, and is not available for the production of large quantities of iron.

Sec. 20. Nearly all the iron used to-day is reduced from ore in the **Blast-furnace.** Fig. 3 shows a vertical section of a blast-furnace. The height varies from 40 to 100 feet, and the diameter at *M* varies from 12 to 25 feet. The inside form varies with the kind of ore and fuel used, and with the pressure and quantity of air of the blast.

A blowing engine supplies air, at a pressure of from 5 to 15 pounds per square inch, to the large pipe, *P*, which surrounds the stack. At intervals of the circumference of this pipe smaller pipes convey the air to the tuyeres, *T*, which deliver it into the furnace. The oxygen of the air combines with carbon of the fuel and

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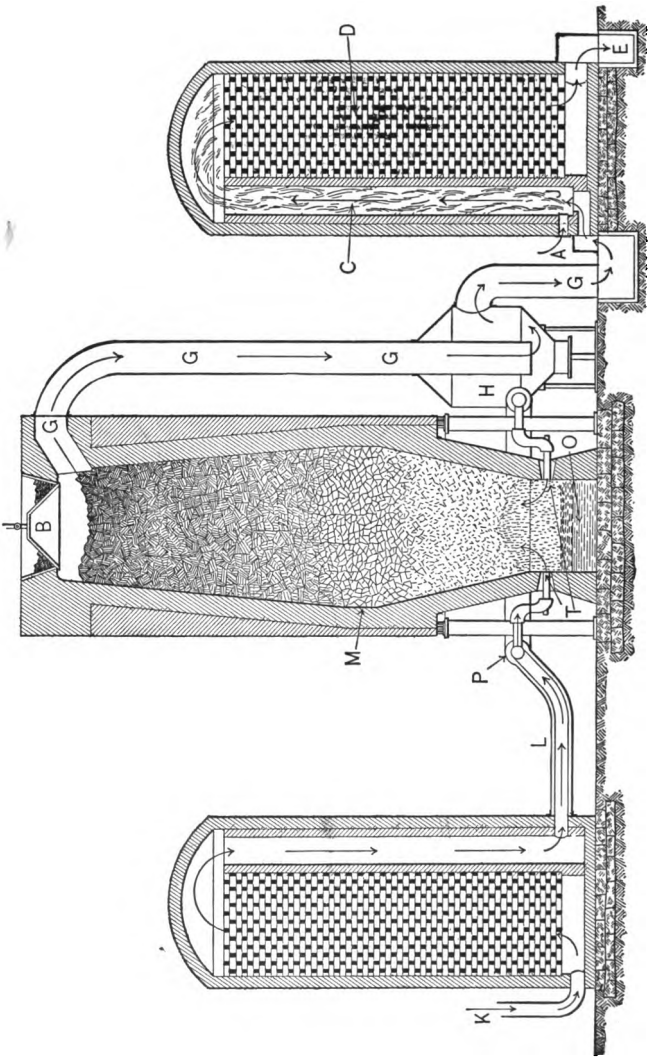

FIG. 3.

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forms carbon dioxide, which is almost immediately reduced, in the presence of carbon with restricted oxygen supply, to carbon monoxide. There is a constantly ascending current of carbon monoxide and nitrogen through the constantly descending solid materials.

The "bell," *B*, prevents the escape of gas from the top of the stack, and insures its delivery into the pipe, *G*. Solid materials to be introduced into the furnace are placed in the annular space above *B*, and the latter, which is controlled by power, is lowered periodically and the charge drops into the furnace.

The function of the blast-furnace is to change iron ore into pig iron.

Pig Iron is iron carrying from 3 to 10% of carbon, silicon, manganese, sulphur, and phosphorus, either chemically combined or mechanically mixed.

The blast-furnace, therefore, provides for—

(*a*) The removal of volatile constituents of the ore.

(*b*) The reduction of the iron oxide of the ore.

(*c*) The removal of the solid earthy constituents of the charge.

It also provides carbon, silicon, manganese, sulphur, and phosphorus under proper conditions for absorption by the iron,

In order that the earthy solids of the ore shall combine with the flux into a readily fusible slag, silica, alumina, and lime must be present. If the ore carries

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silica and alumina, it is only necessary to introduce lime, and the flux is limestone. If an ore contains silica only, alumina may be introduced with lime; or, siliceous and aluminous ores may be mixed and fluxed with limestone.

Sec. 21. **Chemical Changes in the Blast-furnace.*** —Ore, coke, and limestone are charged into the top of the stack and descend slowly to the crucible, *O*, at the bottom. The ore is first roasted,† and then, when the temperature has reached about 400° F. the reduction of iron oxide by carbon monoxide begins slowly and continues at an increasing rate till the temperature reaches about 1100° F., when the reduction is probably nearly complete. The ore has now become a sponge of metallic iron mixed with silica, alumina, etc. But at this latter temperature the flux, which is limestone, $CaCO_3$, begins to give off CO_2, and the lime, CaO, thus produced comes in contact with the silica and alumina of the reduced ore, and they descend together till a temperature is reached at which they combine to form a fusible slag, which melts and leaves the iron sponge.

Introduction of Carbon.—In the meantime a deposition of carbon upon the iron sponge has been going on. This may be explained as follows: When carbon

* Iron (The Metallurgy of), by T. Turner; J. B. Lippincott Company.

† See Sec. 18.

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monoxide passes over metallic iron at a temperature of about 750° F., the carbon monoxide is decomposed, solid carbon is deposited, and carbon dioxide and ferrous oxide are formed. This is what occurs in the blast-furnace when the temperature of about 750° F. is reached by the metallic iron sponge. Then, as the temperature rises, ferrous oxide is reduced again by carbon monoxide, or by solid carbon, the carbon dioxide passes on upward with the gas-current, and the iron sponge remains impregnated with carbon. As this passes on down with increasing temperature, iron carbide is formed, which is fusible at a much lower temperature than pure iron; a temperature which is reached below *M* in the blast-furnace. Therefore the descending iron carbide is raised to its fusion temperature and melts and falls into the crucible *O*.

Introduction of Silicon.—At very high temperatures, in the lower part of the furnace, where carbon and silica and metallic iron are in contact, a portion of the silica is reduced, and the resulting silicon is taken up by the iron. This change is favored by (*a*) high temperature, (*b*) excess of silica in the charge, and (*c*) deficiency of lime in the slag. Usually not more than 5% of the silica of the charge is reduced.

Introduction of Manganese.—The manganous oxide of the ore is not reduced by carbon monoxide, but is in part reduced by carbon at high temperatures, and the resulting manganese combines with the iron. The

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unreduced manganous oxide passes into the slag. Certain ores, like New Jersey Franklinite, contain very large proportions of manganous oxide, and the product of their smelting is Spiegel-Eisen, containing from 5 to 25% manganese.

Introduction of Sulphur.—Only a small part of the sulphur in the charge, which is chiefly in the coke as iron sulphide, FeS, appears in the pig iron, the rest passing into the slag as calcium sulphide. The amount of sulphur that the iron can take up depends upon the capacity of the iron itself for sulphur, and also upon the amounts of silicon and manganese present. Both of these substances seem to crowd out sulphur to a certain extent. High furnace temperature tends to reduce the amount of sulphur in the pig iron. Also basic slag, i.e., slag with excess of lime, combines readily with sulphur, thereby reducing the amount absorbed by the iron.

Introduction of Phosphorus.—The phosphorus of the charge is usually in the ore in the form of calcium phosphate. This is not changed by carbon monoxide. But when the part of the furnace is reached where the slag is formed, the calcium phosphate is reduced in the presence of solid carbon. The lime goes to the slag; the phosphoric anhydride is broken up with formation of carbon monoxide and iron phosphide. Practically all of the phosphorus of the charge appears in the pig iron.

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Descent of Coke.—Coke is the fuel almost universally used in "hot-blast" furnaces. As the coke descends it is dried and raised in temperature. It meets carbon dioxide, which may come from the reduction of iron oxide, or from the roasting of carbonate ore, or from the roasting of limestone. The carbon dioxide is reduced to carbon monoxide with absorption of heat. The resulting carbon monoxide may take part again in reduction, or, if it be near the top of the stack, may pass off unchanged with the gas-current. The coke *may* also supply part of the carbon for formation of carburetted iron, and it also helps in the reduction of silica and phosphoric anhydride. When it reaches the vicinity of the tuyeres it burns to CO and evolves the heat necessary for the operation of the furnace. All of the carbon of the coke appears either in the pig iron or in the gases issuing from the top of the stack.

Sec. 22. The combination of iron, carbon, silicon, manganese, sulphur, and phosphorus is fusible at a temperature which is reached a little below *M* in the blast-furnace. Hence fusion occurs and the melted substance falls into the crucible, *O*, together with the fluid slag. The iron and slag separate because of their difference in specific gravity, the slag floating on the top. When a sufficient amount has accumulated, the slag is tapped out through the "cinder-notch," allowed to cool, and transferred to the "cinder

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dump." The iron is tapped out through a hole low down in the crucible and allowed to run out through properly formed sand channels, where it cools as pig iron.

Sec. 23. From what precedes, it follows that a continuous current of gas flows from the top of the blast-furnace stack. The chief constituents of this are nitrogen, carbon dioxide, and carbon monoxide. When the furnace is properly regulated, the carbon monoxide equals about 25% of the issuing gas. It is therefore a gas fuel. A portion of this is conducted to the boiler furnaces to make steam to run the blowing engines and other auxiliary machinery. The rest is used for heating the blast.

Sec. 24. **Hot Blast.**—In early blast-furnaces the blast entered the furnace nearly at the temperature of the outside air. Cold blast is still used in furnaces for the smelting of some special grades of iron.

Heating the blast on its way from the blowing engine to the tuyeres results in:

(*a*) **Economy of Fuel,** because the blast is heated by the waste gas fuel from the top of the blast-furnace stack, and less fuel needs to be burned in the furnace to maintain a given temperature.

(*b*) **Increased Capacity,** because, since less coke is charged, ore and flux may take its place.

(*c*) **Grayer Pig Iron.**—The furnace temperature is higher with hot blast, and this favors the reduction of

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silica, and the presence of silicon in the iron causes a large part of the carbon to crystallize out as graphite, i.e., it renders the iron gray.

The first method of heating the blast was to pass it through cast-iron pipes, which were enclosed in a furnace and maintained at the highest temperature that is safe for the material of the pipes. This temperature, however, is only about 900° F. In order that a higher blast temperature may be reached, special hot-blast stoves have been designed. The Cowper type is shown in Fig. 3. It consists of a cylindrical shell of iron plates lined with fire-brick. *C* is a combustion-chamber, and *D* is a chamber filled with "chequer work." The gas fuel from the top of the stack passes through the pipe *G*, the dust-separator *H*, and into the combustion-chamber at *J*. Here it meets air which enters at *A*, and combustion takes place. The heated products of combustion pass down through *D* and on through *E* to the chimney. This process is continued till all the combustion-chamber and the chequer work are raised to the temperature of combustion. In the meantime the air from the blowing engine enters the other stove (which has been previously heated) at *K*, passes up through the chequer-work chamber, and down through the combustion-chamber. The air gains heat from the chequer work and is thereby raised to a temperature somewhere between 1000° and 1500° F. It then passes through *L* and *P* to the

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tuyeres, *T*, where it enters the furnace. When this stove is cooled down so that the blast is insufficiently heated, properly arranged valves are changed, and the gas burns in the stove at the left, while the blast enters through the stove at the right.

Since the action of the blast-furnace is continuous, there must be at least three stoves, so that any one may be put out of service for cleaning or repairs.

Sec. 25. There are some blast-furnaces that use charcoal exclusively as fuel, with cold blast. The product is white iron. Because of the lower temperature in the furnace less silica is reduced, and less silicon absorbed by the iron. Because of the small amount of silicon the carbon combines with the iron, instead of separating as graphite, and the iron fracture is white. This iron is used for chilled car-wheels, malleable cast iron, etc.

Sec. 26. **Pig Iron** from the blast-furnace goes either (*a*) to the foundry to be converted into castings, or (*b*) to the puddling mill to be converted into wrought iron, or (*c*) to the Bessemer mill to be converted into Bessemer steel, or (*d*) to the open-hearth furnace to be converted into open-hearth steel.

Sec. 27. In the **Foundry** pig iron is melted, with very little chemical change, and poured into sand moulds, where it solidifies in the required form. The material is now called **Cast Iron.**

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The pig iron is melted in a cupola-furnace. See Fig. 4. This consists of a plate-iron shell lined with fire-brick and supported upon standards. Double doors, *A*, opening downward, are closed and held in

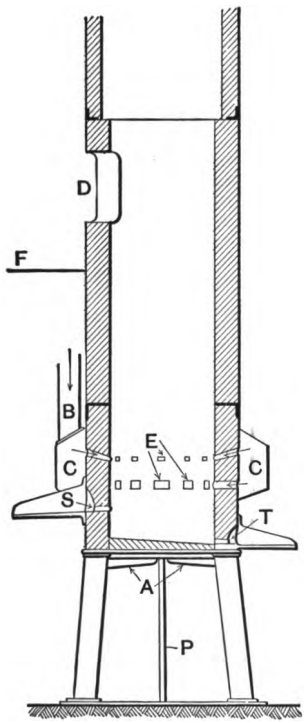

FIG. 4.

position by a prop, *P*, and a sand bottom is rammed into place with a slope toward the tapping-hole, *T*. The top of the cupola is open.

A fan or blower supplies air-blast at a pressure of

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from 5 to 10 ounces per square inch. The air enters through the pipe *B* and passes into the furnace by way of the chamber *C* and the openings *E*.

The charge is elevated to a platform, indicated at *F*, and is introduced into the furnace through the charging-door *D*. Kindling and wood are first laid upon the sand bottom. Upon this the "bed" of coke is charged, and then alternate layers of iron and coke till the level of the charging-door is reached. The fire is lighted and the blast turned on. The coke burns, and the iron melts; and as the top of the charge settles gradually, more iron and coke are "charged on."

The melted iron collects in the bottom and is drawn off periodically at *T* into a receiving ladle, from which it is distributed. Since the hot iron comes in contact with the air-blast there is always silica produced by the oxidation of some of the silicon. Also a considerable amount of silica sand is introduced into the cupola adhering to the pig iron. If the cupola only runs one or two hours a day, as in small foundries, the silica does not interfere with operation. But for long or continuous running it is necessary to include limestone with the charge for a flux, and to tap off slag at *S*.

After all the iron to be melted has been charged into the cupola, the drawing off of melted iron continues and the charge settles down till the cupola is empty except for slag and a little iron. The blast is then stopped, the prop, *P*, is knocked out, the doors,

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A, swing down, and the residue of slag and iron drops out.

Sec. 28. **Puddling Process.**—Both pig iron and wrought iron contain silicon, manganese, carbon, sulphur, and phosphorus; but in pig iron the sum of these is usally from 3 to 10%, while in wrought iron their sum does not usually exceed 1%. The object of puddling is to change pig iron into wrought iron. The process must therefore provide means for the removal of these substances. The removal is effected by oxidation and the puddling process is carried on in a reverberatory furnace. This furnace requires description.

See Fig. 5. *A* is a fire-box provided with a grate

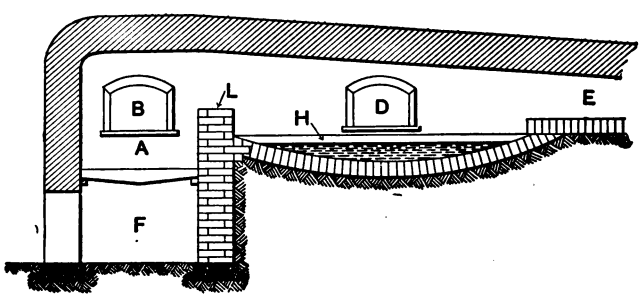

FIG. 5.

upon which solid fuel is burned. *H* is a hearth in which the metallurgical operation is carried on. *E* is a passage connecting with the stack. *F* is the ash-pit, and *B* and *D* are doors for the introduction of fuel and the material to be treated in the hearth. The material

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in the hearth is heated by the hot gases which pass over it, and also by heat reflected from the highly heated refractory material of the furnace roof. Solid fuel burns on the grate, and the air-supply through the ash-pit is under control. If air-supply were just sufficient for perfect combustion, the resulting carbon dioxide and nitrogen, at a temperature corresponding to the calorific intensity of the fuel, would pass over the hearth and give up part of their heat to the furnace walls, and to the material in the hearth, and then go on at lower temperature to the stack. But if air-supply be more restricted, carbon monoxide will result, which will burn in the hearth with air admitted above the fire or through the bridge-wall *L*. In this case the fire-box becomes a gas-producer, and the gas burns in the hearth.

The flame which passes over the hearth of this furnace may be made an *oxidizing*, a *neutral*, or a *reducing* flame. Thus, by a free admission of air through the fire or about it complete combustion of all carbonic oxide is insured, and an excess of oxygen is carried over the hearth with the products of combustion. This results in a tendency to oxidize materials in the hearth. If the admission of air be so regulated as to supply only just enough oxygen to complete the combustion of all carbonic oxide, the flame will be neutral, i.e., it will not tend either to give out or to take up oxygen. If the air-supply be restricted below the fire,

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carbonic oxide will result from the incomplete combustion; and if no air be admitted above the fire this carbonic oxide will pass over the hearth with a tendency to take up oxygen from the materials there, or to *reduce* them.

In the form of reverberatory furnace used for puddling, the bottom of the hearth is made up of cast-iron plates which are covered to a depth of about three inches with a lining or "fettling" composed of silica and oxide of iron. The fettling is put in as follows: Tap-cinder (which may be represented thus: $2FeO, SiO_2$) is charged in upon the iron plates, spread evenly, and subjected to a temperature high enough to soften it in the presence of oxygen. The FeO takes up oxygen and becomes Fe_2O_3. This will not remain in combination with the silica, and hence the fusible silicate is converted into infusible ferric oxide and silica. Then scrap iron is charged in and subjected to an oxidizing flame. It is thereby changed to magnetic oxide, which is raised to a welding heat and spread smoothly over the hearth bottom.

If the hearth were lined with silica, the lining would be fluxed away by the ferrous oxide formed during the puddling process, with considerable loss of iron. Also it is impossible to remove phosphorus in the presence of free silica.*

* See Sec. 32.

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There are two puddling processes: **Dry Puddling** and **Wet Puddling.** In the first, and less used process, white pig iron is heated in the hearth of the reverberatory furnace and subjected to the action of an oxidizing flame. White iron differs from gray iron in passing through an intermediate pasty condition before melting. During the passage through this condition, the iron is constantly stirred with a "rabble" or iron bar, which is inserted through a hole in the door *D*. The order in which oxidation of substances occurs is silicon, manganese, carbon, iron. A considerable part of the silicon and manganese is oxidized during the melting and ferrous oxide also is formed. The silica and manganous oxide combine to form silicate of manganese, a fusible slag, and if silica is still left free it combines with ferrous oxide to form silicate of iron or slag. When the silicon and manganese are completely oxidized, the oxygen attacks the carbon and iron at the surface of the bath of metal. The resulting carbon dioxide passes off to the stack, and ferrous oxide acts as a carrier of oxygen, i.e., it is mixed with the bath and gives up its oxgen to combine with the carbon of the iron carbide, and the result is that carbon monoxide bubbles up to the surface of the bath and burns there to carbon dioxide, while the iron of the oxide and carbide remains in the hearth. This continues till the carbon is almost entirely removed. Then, because of the raising of the

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fusing-point, the iron begins to solidify and is collected in a "puddle ball," which is really a sponge of wrought iron with its interstices filled with slag. This is raised to a welding temperature, and put through a "*squeezer*," where the slag is squeezed out and the component parts are welded together. It is thereby converted into a "bloom." This bloom is then put through a "roughing train" of rolls and is thereby converted into "muck bar," which is cut up, piled, reheated, welded under a hammer, and rolled into "merchant bar." This piling, heating, and rolling is sometimes repeated, with a resulting product of finer fibre and increased strength and ductility.

In wet puddling, the more commonly used process, gray iron is used, and it is allowed to become entirely fluid before it is "rabbled." The oxide of iron in this process, instead of being formed in the furnace, is derived from the fettling or introduced in the form of "mill scale,"* or slag from previous heats that are rich in ferrous oxide or some kind of rich ore.

The chief distinction, then, between the two puddling pocesses is that in dry puddling the oxygen is supplied by the air, while in wet puddling the oxygen comes from the oxide of iron which is introduced with the pig iron.

In order that the phosphorus may be removed it is

* The iron oxide that scales off from iron when it is hammered or rolled.

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necessary that there should be an excess of ferrous oxide in the fettling and the slag. Then phosphorus is oxidized to P_2O_5, and this combines with FeO to form ferrous phosphate ($Fe_3P_2O_8$). This is the form in which the phosphorus appears in the slag. If there had been uncombined silica present in the slag the phosphoric anhydride would have been reduced again to iron phosphide and the phosphorus would have appeared in the iron instead of in the slag.

Sulphur is removed in the puddling process, but the manner of its removal is not clearly understood. The sulphur exists in the pig iron as iron sulphide, and it appears in the slag in the same form. A basic slag (i.e., slag with excess of ferrous oxide), and a long period of contact of iron with the slag, are favorable to the removal of sulphur.

Sec. 29. A process is sometimes used which is intermediate between the blast-furnace process and the puddling process. It is called **refining.** It removes most of the silicon and manganese, but stops the process of removal before the iron becomes too infusible to be cast. The furnace for this process is a rectangular hearth with tuyeres on two sides bringing air under pressure. Melted iron from the blast-furnace may be run into this furnace and subjected to the oxidizing air-blast, or pig iron may be charged in with coke to melt it. In either case iron oxide may be introduced to hasten the removal of silicon and

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manganese. The iron, after completion of the treatment, is run out into sand moulds, where it cools in the form of plates. These plates are broken up and taken to the puddling-furnace, where the conversion into wrought iron is completed. The refinery changes gray pig iron into white pig iron, because it removes the silicon which causes much of the carbon to change into graphite during cooling.

Sec. 30. **Processes for Making Tool-steel from Wrought Iron.**—The difference between wrought iron and tool-steel is in the amount of carbon contained.

Wrought iron has from 0.1% to 0.3%
Tool-steel " " 0.5% to 1.5%

The change from wrought iron to tool-steel is therefore to be effected by addition of carbon.

Cementation Process.—Bars of very pure wrought iron, about $\frac{5}{8}'' \times 5'' \times 12$ feet long, are packed in refractory boxes about 3 feet wide by 3 feet deep, with alternate layers of rather finely divided charcoal. These boxes, which are sealed up to exclude the air, are in a furnace where the temperature is gradually raised to about 3000° F. and maintained for several days, and then allowed to cool down. Iron in contact with carbon at high temperature tends to absorb carbon slowly, and it is found that the bars, after treatment as described, are changed to steel. The carbon, however, is not uniformly distributed, the structure is

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coarse, and the material brittle. This material (called **blister-steel**) is changed to tool-steel by the **crucible process,** as follows:

The blister-steel is broken up into small pieces and charged into refractory crucibles about 2 feet high, with an average diameter of about 10″. These crucibles are placed in a furnace, usually of the Siemens regenerative type, where the melting temperature of steel can be attained, and their contents is fused. This fluid steel is then cast into an ingot, which is homogeneous chemically, but of coarse, crystalline structure, because of its *heat treatment.* It is then reheated and hammered into standard sizes and forms, and the mechanical working gives it a fine homogeneous structure.*

The cementation process is often omitted and wrought iron is charged into the melting crucibles together with cast iron which is free from sulphur and phosphorus. Coke or charcoal may be charged also to prevent oxidation at the surface, and to serve as a source of carbon. Some carbon may be absorbed from the crucibles which contain either plumbago or finely divided coke. Either ferro-manganese or spiegeleisen † is introduced into the crucible because the

* Explained in Chapter IV.

† A product of special blast-furnaces which contains iron, carbon, and manganese. The manganese is present in percentage ranging from 10 to 80. With high manganese it is called ferro-manganese. With low manganese it is called spiegeleisen.

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manganese reduces any iron oxide that may be present, and removes gas or causes it to go into solution, thus preventing porosity. The carbon of the ferro or spiegel increases the carbon of the steel. The melter regulates these sources of carbon so as to insure close approximation to the required grade of the product.

Sec. 31. **The Bessemer Process.**—Bessemer steel is very similar to wrought iron in chemical composition, but usually contains a little more carbon. The structure, however, is different, because of the difference in the method of manufacture. Thus wrought iron is built up from small particles of iron covered with slag. The slag is not entirely removed and the process of rolling draws out the particles into threads that are still surrounded by slag. This gives wrought iron the appearance of a fibrous structure. But Bessemer steel is cast into a solid ingot and then drawn down to the required shape and size. It therefore shows the crystalline structure of the iron itself.

The Bessemer process changes pig iron into steel containing from 0.1% to 0.6% of carbon. This change is accomplished in a vessel called a **converter.** See Fig. 6.

The vessel is made up of riveted iron or steel plates, and is lined with "ganister."* The converter is mounted upon trunnions, *A*, *A*, and can be turned

* See Section 16.

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about the axis of the trunnions into any required position. Cold air from the blowing-engine, at a pressure of 20 to 25 pounds per square inch, enters at E, follows the passage shown to F, whence it passes into the con-

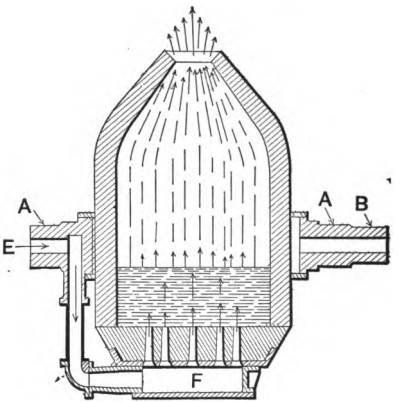

FIG. 6.

verter through holes about $\frac{3}{8}''$ diameter that pierce the conical fire-bricks shown in the converter bottom.

The Bessemer plant includes cupolas for melting the pig iron. The melted iron is conveyed to the converters either through properly formed channels with refractory linings, or in ladle-cars running upon a track. Sometimes these cars transport the fluid iron directly from the blast-furnace to the converter.

The converter is turned on its side, and a charge of iron is run in. It is then turned into a vertical position and a valve opens automatically to turn on the blast, and the air is forced through the bath of iron. The

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results are as follows: The oxygen of the air combines with the oxidizable substances of the bath; and iron being in great excess, ferrrous oxide is formed throughout the entire "blow." But silicon is also present, and the ferrous oxide is reduced by it, and silica is formed thus, as well as by direct combination of silicon with the oxygen of the air. Manganese is also present and oxide of manganese is formed, and this combines with silica to form silicate of manganese, a fusible slag. If the silica is in excess, some fusible silicate of iron is also formed. During this period brilliant sparks of slag are thrown from the mouth of the converter.

When all the silicon and manganese are removed, the carbon begins to be oxidized, directly by the oxygen of the air, and indirectly by the oxygen of the ferrous oxide. Carbon monoxide is formed, which passes off from the bath, and on reaching the mouth of the converter burns to carbon dioxide in a long, bluish flame. When the oxidation of the carbon is complete, there is no substance left to reduce the iron oxide formed, and reddish fumes appear at the mouth of the converter, and the process is immediately stopped by turning the converter on its side.

The converter now contains nearly pure iron, and although its fusion temperature is about 4000° F., it remains fluid. The fuel which, by its oxidation or combustion, has raised the temperature of the converter from the melting-point of pig iron to that of

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wrought iron, is the silicon, manganese, and carbon of the pig iron.

When the first experiments were made on the Bessemer process, it was thought that the blow could be stopped at the right point to leave in the amount of carbon necessary to make steel; but it was found impossible to get uniform results, and also it was found that the resulting metal was brittle and worthless.

This was due to the fact that iron oxide remained in the metal, and that some gas was occluded, causing porosity. To overcome these difficulties, the blow is continued till the carbon is completely removed, and a known proportion of spiegeleisen or ferro-manganese is added to effect the recarburization. The manganese reduces the iron oxide, and, in some not very well understood way, removes the occluded gases or causes them to go into solution. After the addition of the spiegel or ferro, the contents of the converter is poured out into a ladle, from which it is cast into ingots, which are rolled into rails, or plates, or into blooms, which are to be rolled or forged into required forms.

Sec. 32. **The Basic Bessemer Process.**—During the blow as described, phosphoric acid and ferrous oxide are formed simultaneously, and these combine to form phosphate of iron, or ferrous phosphate; thus $3FeO + P_2O_5 = Fe_3P_2O_8$. But this is reduced again to iron phosphide by **silicon** and **carbon**, and therefore little

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or no phosphorus can be removed until after the complete removal of these substances from the metal in the converter. Ferrous phosphate is also reduced by **silica**, because the silica has greater affinity for ferrous oxide than phosphoric acid has, and so ferrous silicate is formed and phosphoric acid is left, which is probably reduced to iron phosphide by the metallic iron, with formation of ferrrous oxide.

The lining of the Bessemer converter described is largely silica, and therefore silica is always present, and no phosphorus can be removed in a converter with a "ganister" or "acid" lining. It is necessary, therefore, to use pig iron for this process which is very low in phosphorus, since the presence of phosphorus in the product in any considerable amount is very undesirable.

The fact that a large proportion of the iron ore of the world contains phosphorus, which is not removed in the blast-furnace, made it desirable to find a way to eliminate phosphorus in the steel-making process. This led to the invention of the Basic Bessemer Process, in which a lining of lime and magnesia is substituted in the converter for ganister. The only free silica, then, is that which results from the oxidation of the silicon in the pig iron. This combines with the lime or magnesia of the converter lining, or with that which is charged into the converter during the blow, and forms a stable slag, the silica being

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thereby rendered powerless to reduce the ferrous phosphate.

The lime or magnesia present then replaces the ferrous oxide of the ferrous phosphate, forming calcium or magnesium phosphate, which is probably the form in which the phosphorus chiefly exists in the slag.

In the acid process iron is not usually used which contains less than 2% of silicon, because the combustion of at least that amount of silicon is necessary to produce a sufficiently high temperature in the converter.

In the basic process silicon is an undesirable element, since all the silica produced must be neutralized by lime, in order that the process shall succeed. For this reason iron with 0.5% silicon is best, and 1.5% is the highest allowable limit. This makes it necessary to substitute some other fuel, and therefore pig iron high in manganese is used. The phosphorus is also a fuel and raises the temperature during the "after-blow." In the basic process little or no phosphorus is removed till after the complete removal of the carbon, and the blow has to be continued after the "dropping" of the carbon flame. The duration of the afterblow is determined from a knowledge of the amount of phosphorus in the pig iron used, or by taking samples at intervals during the afterblow and making physical tests.

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The best pig iron for the basic process contains:

P,	about 3	per cent
Mn,	over 2	" "
Si,	0.5	" "
S, less than	0.1	" "

This is white iron, because of high manganese and low silicon, whereas the high silicon iron used in the acid process is gray.

Sec. 33. **Control of Temperature in the Bessemer Converter.**—Either too high or too low temperature of the steel at pouring results in porosity, and therefore this temperature must be carefully regulated. If iron too high in silicon be used in the acid process, too high temperature results, and conversely.

In the basic process the difficulty is usually to keep the temperature high enough. If the temperature is too high, it may be reduced by charging in scrap-steel from the mill, which is thus remelted, absorbing surplus heat, and is rendered available for use. The temperature is also sometimes reduced by admitting a small amount of steam into the blast-pipe.

If the temperature becomes too low, the converter may be inclined, as shown in Fig. 7, during the burning out of the carbon. When the converter is vertical the carbon monoxide formed burns at the mouth of the converter, and the heat evolved is lost as far as raising the temperature of the inside of the converter is con-

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cerned. In the inclined position, however, part of the air of the blast passes through the metal bath and forms carbon monoxide, and part passes through the uncovered tuyere holes and furnishes oxygen to the carbon monoxide, and carbon dioxide is formed; i.e.,

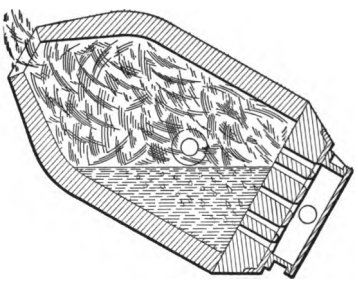

FIG. 7.

combustion occurs inside of the converter, and the heat developed raises the temperature of the metal bath.

Sec. 34. **Graphical Representation of the Basic Bessemer Process.**—Fig. 8 is copied from Wedding's "Basic Bessemer Process," * page 143. The diagram is plotted from the results of experiments and shows the history of a blow in a basic converter. Horizontal distances from *O* represent time, each division corresponding to one minute. Vertical distances from *O* represent percentages of the substances to be removed. Therefore the curves represent the change in percentage of the substances during the blow.

* Translated by Phillips and Prochaska. E. & F. N. Spon, Publishers, London.

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The silicon is reduced very rapidly from 1.2% at the beginning of the blow; and after six minutes only 0.1% remains. From this point on the silicon is slowly reduced to zero.

The manganese is reduced less rapidly than the silicon, changing from 1.05% at the beginning to 0.15% after nine minutes. It then remains nearly constant

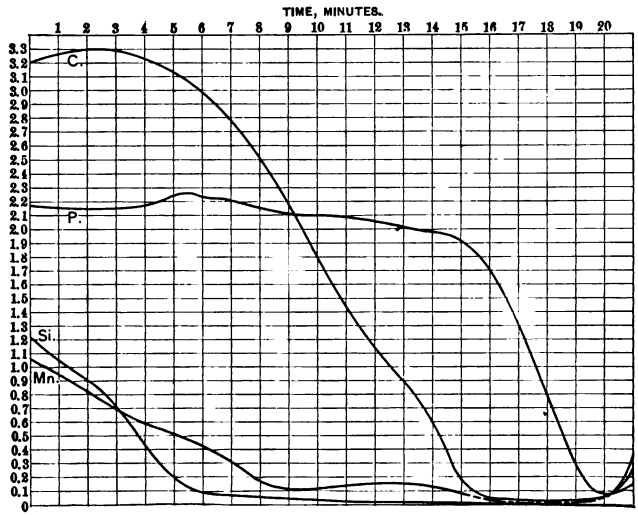

FIG. 8.

during the carbon reduction, and then becomes less than 0.1%.

There is but little change in the carbon until most of the silicon is removed and then the curve drops rapidly, and the removal is practically complete in sixteen minutes. Up to this time there has been little change in the phosphorus. This is of course because

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the ferrous phosphate is reduced by carbon. From this point the removal of phosphorus is very rapid, being practically complete after the blow has continued twenty minutes.

The curve of sulphur was shown on the original diagram, but it was not copied, as the quantity of sulphur remained nearly constant, its value being less than 0.1%. The blow ends at the twenty-minute line, and the curves beyond show the effect of introducing spiegeleisen.

Sec. 35. Fig. 9* gives the history of an acid Bessemer blow. The amount of silicon is very low for the acid process. Phosphorus remained practically constant at 0.1%, and sulphur at 0.06%. Figs. 8 and 9 are plotted on the same scale for comparison. The blow ends at 9m. 10s., and the rest of the curve results from the introduction of spiegeleisen.

Sec. 36. **Open-hearth Processes.**—Steel is also made from pig iron in the hearth of a Siemens regenerative furnace. See Fig. 2. The silicon, manganese, and carbon are removed by oxidation, as in the puddling, or in the Bessemer, process. Two processes are carried on in open-hearth furnaces: first, Siemens, or "pig and ore," process; second, Siemens-Martin, or "pig and scrap," process. These correspond to

* Plotted from experiments of F. Julian at South Chicago works of Illinois Steel Company. See H. M. Howe, Journal Iron and Steel Institute, Vol. II, 1890, page 102.

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wet and dry puddling; the difference being that here the temperature is high enough so that the product is held fluid and cast into an ingot, while in the puddling

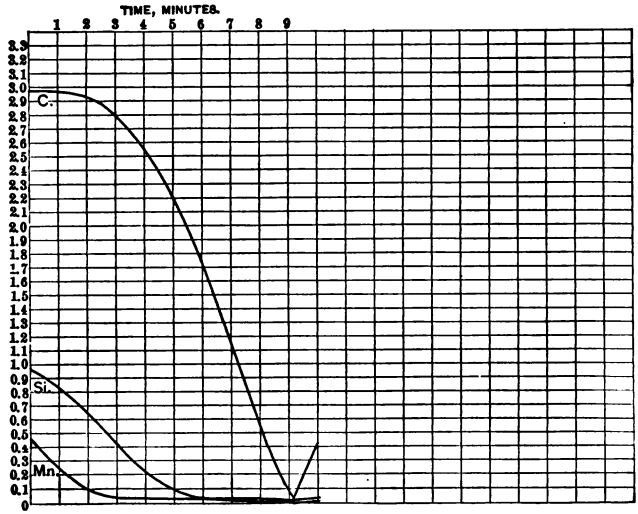

FIG. 9.

process the temperature is such that the product solidifies and must be treated by rolling-mill processes. In the Siemens process pig iron is charged into the hearth and melted, part of the silicon and manganese being oxidized during the melting, and then rich ore is added to supply the oxygen to combine with the remaining silicon and manganese, and the carbon of the iron carbide. When the action is complete the bath of nearly pure iron is recarburized by the addition of spiegeleisen or ferro-manganese, and the manganese reduces the ferrous oxide present, and removes

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occluded gases or causes them to be dissolved as in the Bessemer process.

In the Siemens-Martin process pig iron is charged into the hearth, and melted with partial removal of the silicon and manganese, and then steel scrap is charged into the bath, which melts, and thus the percentage of silicon, manganese, and carbon is reduced by *dilution*. The remaining part of these substances is removed by the direct action of the oxidizing flame, and the indirect action of the ferrous oxide formed at the surface of the bath, and mixed with it. Spiegel or ferro are added as in the Siemens process. Ferro-silicon and ferro-aluminum are sometimes used in place of ferro-manganese for the recarburization, and the removal of iron oxide and the prevention of porosity.

Either acid or basic lining may be used in the furnace in which the open-hearth processes are carried on. With the acid lining no phosporus is removed and hence low-phosphorus pig must be used. With the basic lining the phosphorus is removed as in the basic Bessemer process.

Sec. 37. **Ductile Castings.**—Many machine members of somewhat complicated form need to be of materal whose ductility and resilience are high. If such parts were to be made in large numbers, they could be produced by the process of casting much cheaper than by the process of forging. For this reason much attention has been given to the produc-

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tion of castings of ductile material. The most important resulting processes are those for the production of, first, Malleable Castings; second, Steel Castings. Some of the grades of brass and bronze give castings which are strong and ductile, but the high cost puts them out of competition for many purposes.

1. The process for the production of **Malleable Castings.**—White cast iron, i.e., iron with all the carbon in combination, is melted and cast into the required forms. These castings, which are hard, weak, and brittle, are packed in cast-iron boxes in the midst of coarsely powdered oxide of iron, usually hæmatite ore or hammer-scale. These boxes are sealed and exposed to a temperature of full redness in a reverberatory oven for from three to six days. They are then slowly cooled down, and the cast iron is changed to something that is very much like wrought iron in strength, ductility, resilience, and softness.

There are two reasons for this change: first, the total carbon is reduced; and second, the combined carbon is nearly all changed to very finely divided graphitic carbon.

The following analyses * show these changes:

	Total Carbon.	Graphitic Carbon.	Combined Carbon.
Before mallifying..	2.79%	0.177%	2.613%
After mallifying...	1.74%	1.565%	0.175%

* Analyses made by Mr. W. H. McCord at the chemical laboratory of Stanford University.

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The iron for the castings was melted at first in cupolas, with very little chemical change. But it was found desirable to have the total carbon as low as consistent with the retaining of sufficient fluidity for making satisfactory castings. Hence a reverberatory furnace was substituted for the cupola. The iron is melted down in the hearth, and subjected to an oxidizing flame until its carbon is reduced to the allowable minimum, and then it is cast. Because of this change the process became applicable to much larger castings. The chief function of the mallifying process in large castings is probably to change combined carbon to graphitic carbon.

The reduction of total carbon is sometimes accomplished by *dilution;* i.e., scrap steel or wrought iron is charged in with the pig iron.

2. **Steel Castings.**—The melted steel of the open-hearth or of the Bessemer converter is often poured into moulds of very refractory sand, and the resulting castings are called steel castings. Since the "freezing-point" of these castings is about 1000° F. above that of cast iron, the ill effects of shrinkage are greater. Moreover, steel castings are of coarse structure because they are cooled from the fluid state; and to render the structure fine, and the castings strong and ductile, it is necessary to anneal them very carefully.

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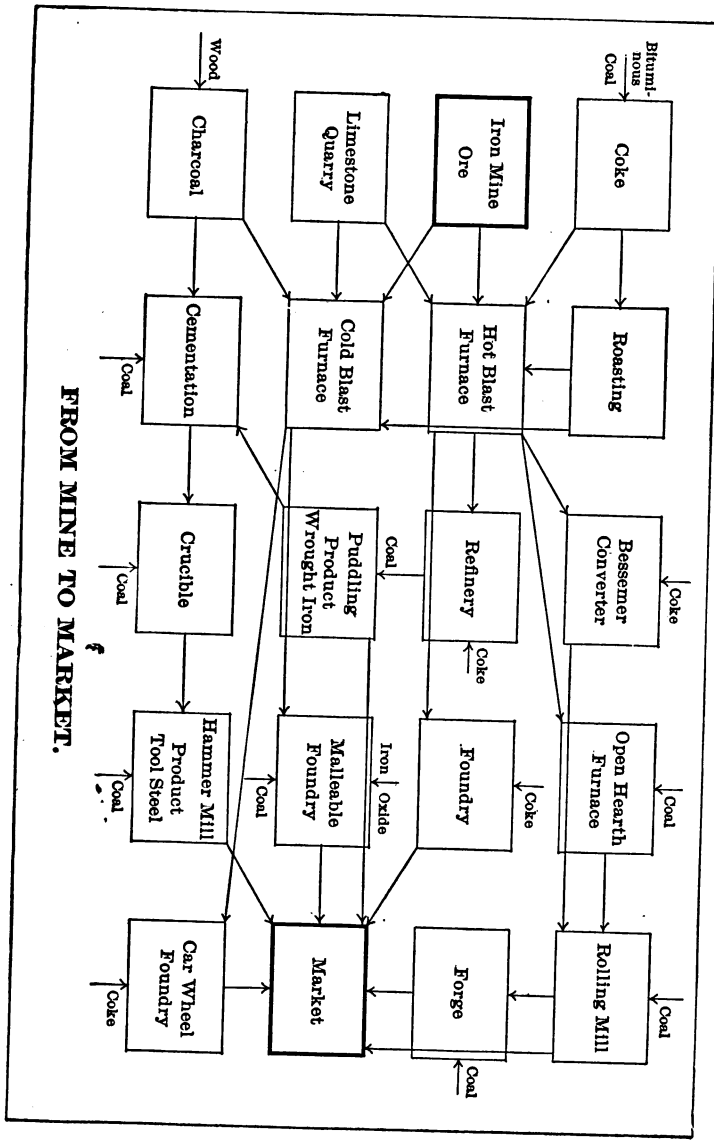

FROM MINE TO MARKET.

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CHAPTER II.

TESTING. STRESS-STRAIN DIAGRAMS.

SEC. 38. **The testing of materials,** and the methods of recording and interpreting results, will be briefly considered, as a preliminary to the study of the physical qualities of materials.

A test-piece of proper dimensions may be made of any material, and may be broken by the application of a force producing tensile, compressive, torsional, or transverse stress. It will be assumed that means are provided for the application of forces of known value; also that any *deformation* of the test-piece may be accurately measured. Let a tension test be considered. The force in this case is applied so that it tends to elongate the test-piece. The elongation which results is called **strain.** The action and reaction between adjacent portions of material is **stress.** Strain is always the deformation which accompanies stress.

It will be found that for every increment of stress there will be an increment of strain. In the early part of the test these will be proportional to each other;

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i.e., **stress is proportional to strain.** This is **Hooke's Law.** After passing a certain limit it is found that this proportionality ceases, the increment of strain becoming much greater for a given increment of stress. This limit is called the **elastic limit** of the material.

If, before reaching this limit, the stress is gradually reduced to zero, the strain will become zero; i.e., the test-piece will return to its original dimensions. This shows that the material is perfectly elastic, since **elasticity is the quality of returning to original dimensions on the relief of stress.** If, however, the elastic limit be passed before the relief of stress, the test-piece will be permanently elongated. This permanent elongation is called **"set,"** or **permanent strain.** The strain which disappears on relief of stress is called **elastic strain.**

If the test be continued, the ratio of stress to strain continually decreases after passing the elastic limit. After a while a point is reached where no further increase of stress can be made, because every effort to increase stress is met by so great yielding. The stress at this point is called **maximum stress**, and it represents the **breaking or ultimate strength** of the material. From this point on there is an increasing strain and a decreasing stress, i.e., the force that is sufficient to produce rupture is a decreasing one.

Up to the time of reaching the maximum stress, all

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units of length of the test-piece share the elongation equally. If the piece were of absolutely equal strength in all sections, it would continue to elongate equally throughout, and would finally yield in all sections at once. This is of course impossible, and the point of maximum stress is really the point at which some local weakness is developed, and where a localization of strain occurs; i.e., the test-piece "necks down," and from that point on till rupture the elongation occurs in the neck, because the *unit stress* becomes greater with the local reduction of cross-sectional area. This does not occur in brittle materials, but stress increases from the beginning of the test till rupture occurs.

The test may be made continuous from the beginning without relief of stress, and if periodical readings of stress and corresponding strain be taken, these variables may be plotted with reference to rectangular axes, and a curve drawn through the points thus located will be the **stress-strain diagram** of the material. The test described is that of a ductile material, and *B*, Fig. 10*a*, may represent the resulting stress-strain diagram. A brittle material gives a diagram entirely different in character. Thus *C*, Fig. 10*b*, may represent a stress-strain diagram of cast iron. If diagrams of different material are plotted on the same scale, their physical qualities may be compared by inspection of the diagrams.

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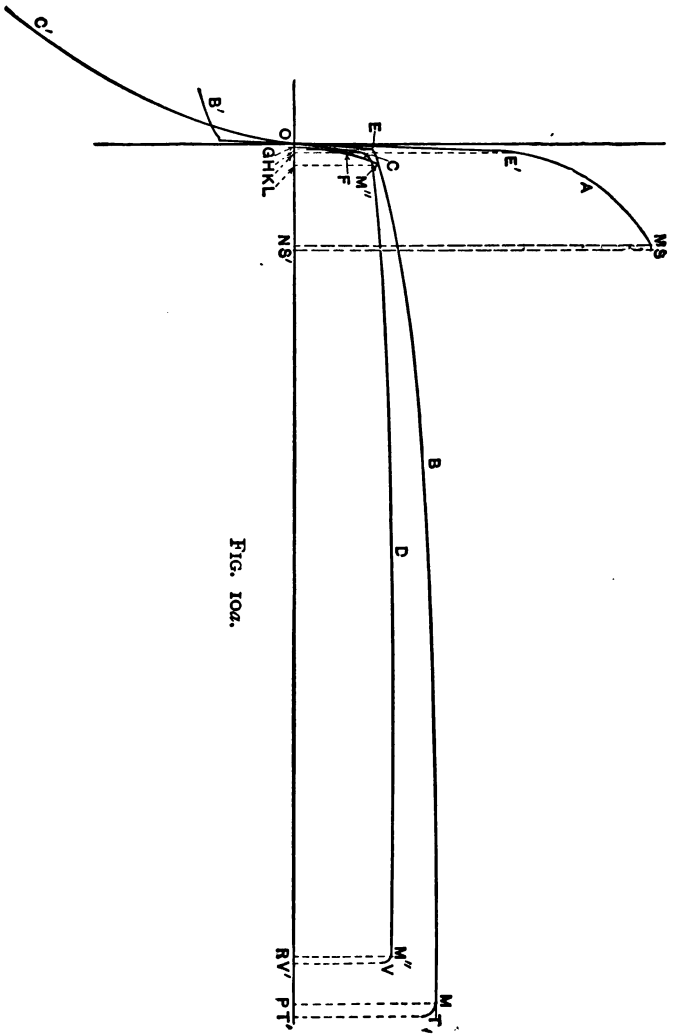

FIG. 102.

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Sec. 39. The physical qualities which appear on the stress-strain diagram are as follows:

1. Strength at elastic limit;
2. Strength, ultimate;
3. Ductility;
4. Stiffness.
5. Elasticity;
6. Resilience, elastic;
7. Resilience, ultimate.

Strength at elastic limit is measured by the stress per unit of cross-sectional area of the piece when the proportionality of stress and strain ceases. **Ultimate strength** is measured by the stress per unit of cross-sectional area when the yielding becomes so great that no addition can be made to the stress. **Ductility** is the quality of being drawn out under stress, and is therefore proportional to the strain, and to the length of the stress-strain diagram on the axis of X. **Stiffness** is the quality of resisting yielding or strain, within the elastic limit. It is therefore measured by the angle which the Hooke's law line makes with the axis of X.* The greater this angle the greater the stiffness of the material. **Elasticity** is already defined as the quality because of which a material regains its original dimen-

* In using this angle as a measure of stiffness the scales for plotting stress and strain must be considered, and diagrams must be plotted on the same scale if they are to be compared.

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sions on the relief of stress. Resilience is the term used to express work done in carrying the test to any point. Thus **elastic resilience** is the work done in straining a piece of material to its elastic limit. **Ulti-**

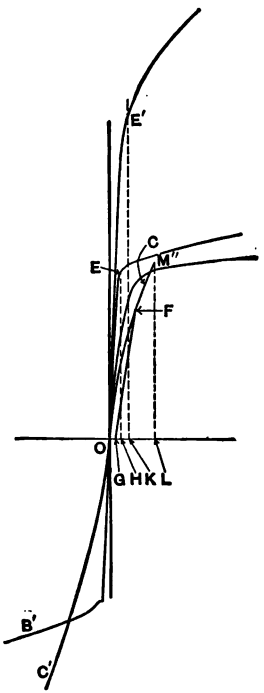

FIG. 10*b*.

mate resilience is the work done in breaking a piece. Since resilience is the work done in producing strain in material, it is therefore a measure of the shock-resisting power of the material, i.e., it is proportional to the energy of a shock or blow which would produce

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the same result. Since the ordinates of the stress-strain diagram represent force and the abscissas represent the space through which the force acts, it follows that the area of the diagram represents work. If, then, a perpendicular be dropped from the elastic limit of the diagram to the axis of X, a triangle will be formed whose area is proportional to the elastic resilience of the material. Thus in Fig. 10*b* the triangle OEH is a measure of the elastic resilience of the material represented by the curve B, and the triangle $OE'K$ is a measure of the elastic resilience of the material represented by the curve A. If a perpendicular be dropped to the X-axis from the end of the diagram, the area bounded by this perpendicular, the curve of the diagram, and the axis of X, will be a measure of the ultimate resilience of the material. Let a comparison of all of these qualities be made for the materials represented by the diagrams of Fig. 10*a*. The curve C rises with a continuous curvature; there is no straight part denoting a period of proportionality of stress and strain; or, in other words, there is no elastic range. There is also no limit of elasticity. If stress were discontinued at F,* the curve would not return upon itself, but would follow an approximate straight line to G, some point to the right of O. This indicates that there is a permanent strain or "set" whose value is OG on the scale assumed for plotting

* See Fig. 10*b*.

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strains. A similar effect would be shown if the stress were relieved at any point in the curve. The material represented by this curve is therefore imperfectly elastic. The same is true of the curve D, which represents copper. The straight initial portion of the curves A and B, however, indicates perfect elasticity.*

The elastic strength of the material of A, Fig. 10*a*, is greater than that of B in the ratio of the ordinate $E'K$ to EH. C and D have no elastic limit, and therefore no value of elastic strength can be assigned. The ultimate strength of A is measured by the ordinate MN; of B by $M'P$; of C by $M''L$; and of D by $M'''R$, and the comparison is easily made.

The *ductility* of A is measured by OS'; of B by OT'; of C by OL; and of D by OV'.

The *elastic resilience* of A is measured (Fig. 10*b*) by the area $OE'K$; of B by OEH. No elastic resilience can be assigned to C and D, since they have no elastic limit.

The *ultimate resilience* of A is measured by the area $OE'MSS'$; of B by the area $OEM'TT'$; of C by the area $OFM''L$; and of D by the area $ODM'''VV'$. Stiffness, being proportional to the angle of the initial part of the curve with the axis of X, is in the following

* It probably is not absolutely true that this material is perfectly elastic. By means of very refined measuring apparatus it is found that nearly all materials take some "set," even when subjected to comparatively small stress. The values, however, are so minute that they may be safely disregarded in the selection of materials for machine parts.

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order, beginning with the stiffest material: 1st, A; 2d, B; 3d, D; 4th, C.

If a material be tested in compression as well as in tension, both stress and strain will be reversed, and stresses will be plotted below the axis of X, and strains will be plotted toward the left from the axis of Y. In Fig. 10*a*, CC' and BB' are stress-strain diagrams of cast iron and wrought iron, both in tension and compression. The compression curve of the wrought iron is almost identical with the tension curve, up to and past the elastic limit. A ductile material cannot, however, be tested to rupture in compression, as the material either "buckles," splits parallel to the axis of the test-piece, or else simply flattens out, thus exposing a constantly increasing area of section to the crushing force. A brittle material breaks in compression by shearing on planes at an angle of about 45° with the axis of the test-piece. The diagram shows that cast iron is a much stronger material in compression than in tension.

Stress-strain diagrams may be also plotted from the data of torsion and transverse tests, as well as from those in which the stress is tensile or compressive.

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CHAPTER III.

CAST IRON.

SEC. 40. Cast iron, as previously stated, is composed of iron, carbon, silicon, manganese, sulphur, and phosphorus. Wrought iron has usually the same qualitative composition, but the substances other than iron are reduced to the very lowest limit possible commercially. The percentage range of these substances in wrought and cast iron is shown in the following table:

	Cast Iron.	Wrought Iron.
Graphitic carbon	1.85 to 3.25	——
Combined carbon	.15 to 1.25	.02 to .25
Total carbon	2.0 to 4.5	——
Silicon	.15 to 5.	0 to .3
Manganese	0 to 1.5	0 to .3
Sulphur	0 to .5	0 to .015
Phosphorus	0 to 1.3	0 to .15

Although the only chemical difference is in the amount of these substances present, yet the physical qualities are entirely different, as is evident from inspection of curves *C* and *B*, Fig. 10*a*. *B* may represent wrought iron, and *C* may represent cast iron. In the change from wrought to cast iron the material, in

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tension, has become weaker, less elastic, less stiff, less ductile, and less resilient; in compression it has become stronger. It would seem that it had become in all respects, except for resisting compression, a less desirable material for use in machine parts. But there is one quality, of which there is no record on a stress-strain diagram, because of which cast iron is invaluable for many machine parts. It is the quality of fusing at a temperature attainable in the foundry cupola. Because of this quality it may be cast into sand moulds, taking required irregular shapes, which cannot be produced by forging; and, after a pattern is once made, a large number of duplicates can be easily and cheaply produced. Where cast-iron machine members are "stress members," the deficiency in strength is compensated by increased cross-sectional areas. Cast iron melts at a temperature of about 2500° F., while the temperature of fusion of wrought iron is about 4000° F., or the highest temperature attainable in the Siemens regenerative furnace. Wrought iron cannot, therefore, be cast (except by special means), and hence has to be shaped by forging. Cast iron cannot be forged at all.

Sec. 41. **The carbon in cast iron** is usually present in two forms: a part is combined or in solution with the iron, and a part is in the form of crystals of graphite distributed throughout the mass of the iron. The reason for this is as follows: When cast iron is in

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a fluid state it has a certain capacity for taking carbon into solution. This capacity is very much reduced when the iron begins to solidify. If, therefore, the fluid iron has absorbed more carbon than it is capable of holding when it is solidifying, the excess will crystallize out as graphite; and, since this crystallization occurs after the iron has ceased to be wholly fluid, the graphite crystals remain suspended in the iron, notwithstanding their less specific gravity.

Sec. 42. The blast-furnace produces different **grades of cast iron,** which are numbered usually from No. 1 to No. 6. No. 1 is very gray at the fracture, and contains a large amount of graphite. No. 6 is white at the fracture, and all the carbon is in the combined state. The intermediate numbers represent the gradation from one to the other. The **total carbon** in cast iron depends chiefly upon the type and conditions of working of the furnace. The distribution of the total carbon between combined carbon and graphite is dependent upon the relative amounts of the other substances present and upon the rate of cooling. The amount of total carbon may also be influenced by the presence of the other substances.

Sec. 43. Cast iron depends for its physical qualities upon the effect of the silicon, manganese, carbon, sulphur, and phosphorus with which it is mixed or combined, and also upon the effect of these substances upon each other.

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The effect of graphitic carbon upon cast iron is to make it weak, both in tension and compression, and to reduce its ductility. This effect is probably due to the fact that the presence of the crystals of graphite interrupts the continuity of the iron structure. Graphitic carbon also renders the iron softer; probably because of the introduction of a softer material, and because the introduction of graphitic carbon is usually at the expense of the combined carbon, which hardens the material.

The increase of combined carbon in pure iron converts it, first into soft steel, then into tool-steel, and finally into white cast iron. The change from pure iron to steel with 1% carbon is accompanied by steadily increasing strength and steadily decreasing ductility. The change from steel with 1% carbon to white cast iron is accompanied by reduction both of strength and ductility.

In Fig. 10*a*, B may be taken to represent the stress-strain diagram of pure iron. The gradual increase of carbon would gradually change it into a material represented by the stress-strain diagram A, the strength being increased from PM' to NM, while the ductility is reduced from OT' to OS'. The compressive strength and ductility would be similarly changed. After passing 1.0% carbon, the addition of further amounts of carbon decreases the tensile strength, still further decreases ductility, and increases the compres-

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sive strength. In Fig. 10*a*, the stress-strain diagram A, which may represent steel with 1% carbon, is, by gradual increase of carbon, converted gradually into the stress-strain diagram C, which may represent white iron. It follows, then, that the effect of combined carbon on cast iron is to decrease tensile strength and ductility and resilience, and to increase compressive strength and ductility and resilience. The effect of combined carbon is greater in degree than that of graphitic carbon, i.e., 0.1% of combined carbon makes changes that are greater in amount than those made by 0.1% of graphitic carbon. If an iron be selected having a certain total carbon (say 3.5%, which is about the average for foundry use), and if all this carbon be in the form of combined carbon, i.e., no graphitic carbon present, the selected iron will be a brittle, hard material, weak in tension and strong in compression. If now a part of the combined carbon be converted into graphitic carbon, the result will be as follows: The tensile strength and ductility and resilience will be increased, because the reduction of combined carbon has increased these qualities, and the increase of graphitic carbon has reduced these qualities, but the reduction is less than the increase, because the effect of the graphitic carbon is less in degree than that of the combined carbon, and the resultant effect is an increase of tensile strength and ductility. The compressive strength, ductility, and resilience are decreased

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because both the decrease of combined carbon and the increase of graphitic carbon tend to produce that result. The material is rendered softer by the reduction of combined carbon and the increase of graphitic carbon. Since this change has increased tensile resilience, it follows that the tensile shock-resisting power of the material is increased, while the compressive shock-resisting power is decreased. The reversal of this process would, of course, produce reverse results. If control of the distribution of total carbon between graphitic carbon and combined carbon were possible, it would become possible to control, at least in part, the qualities of castings so as to fit them for different purposes.

The effect of this conversion of combined carbon into graphite is strikingly illustrated in the process of mallifying white-iron castings.* The process converts the combined carbon of the white iron into the very finely divided graphitic carbon of the malleable castings. The result is the conversion of weak, hard, brittle material into strong, soft, ductile material.

Sec. 44. **The rate of cooling** of castings has a very marked effect upon the crystallizing out of the graphitic carbon. Suppose iron with a low total carbon to be melted and cast into a mould, a part of whose internal surface is of sand, and another part of iron. The part of the melted metal which comes in contact with the

* See Sec. 37.

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iron surface will be "chilled," i.e., cooled far more rapidly than the part which comes in contact with the sand surface (because of the greater conductivity of the iron). The chilled part of the casting will be white in fracture, showing that the carbon is *all* in combination, while the other parts of the casting will be somewhat gray, showing that a part of the carbon has crystallized out as graphitic carbon. The reason for this effect is that the crystals of graphite need some *time* to form, and since the sudden cooling does not allow this time, the carbon all remains as combined carbon.

For certain purposes castings are required with portions of their outside surface very hard to resist wear, while the body of the casting needs to be strong, ductile, and resilient, to resist rupture by shock, and soft so that it may be finished.

A casting with gray-iron body and with white iron at the wearing surface would fulfil these requirements. Such castings are made by chilling the wearing surface, as in case of car-wheels, chilled rolls for iron-mills, etc.

Sec. 45. In homogeneous castings carbon distribution may be controlled by regulating the amount of silicon and manganese present.

If gray iron, low in silicon, be melted, and if manganese be added to it,* the fracture of the cooled

* This may be done by adding ferro-manganese.

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material will be whiter, showing that some graphitic carbon has been converted into combined carbon.

If white iron low in manganese, sulphur, and phosphorus be melted, and if silicon be added to it,* the fracture of the cooled material will be grayer, showing that some combined carbon has been converted into graphitic carbon. Therefore the presence of manganese tends to increase the capacity of iron to hold carbon in combination, while the presence of silicon tends to decrease this capacity.

The presence of sulphur or phosphorus also affects the distribution of carbon. Both tend to increase the amount of combined carbon. If these elements are introduced in any considerable quantity, they render the iron unsafe for stress members of machines, and especially those subjected to shock. Sulphur should not exceed 0.15%, and phosphorus should not exceed 0.3%. These elements, therefore, cannot be used for regulating the carbon distribution. The ill effects, however, which result from the use of silicon or manganese for this purpose are comparatively small. Mr. T. Turner, of Mason College, Birmingham, made a series of experiments to determine the effect of silicon upon cast iron.†

He used iron which had a total carbon as nearly as possible 2%, and with sulphur, phosphorus, and man-

* This may be done by adding ferro-silicon.

† See Iron (The Metallurgy of), T. Turner, page 192.

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ganese quite low; and, by means of ferro-silicon, added successively increasing amounts of silicon, and then subjected the products to chemical and physical tests. The results of these tests as to tensile and compressive strength and hardness are plotted in Fig. 11. At first

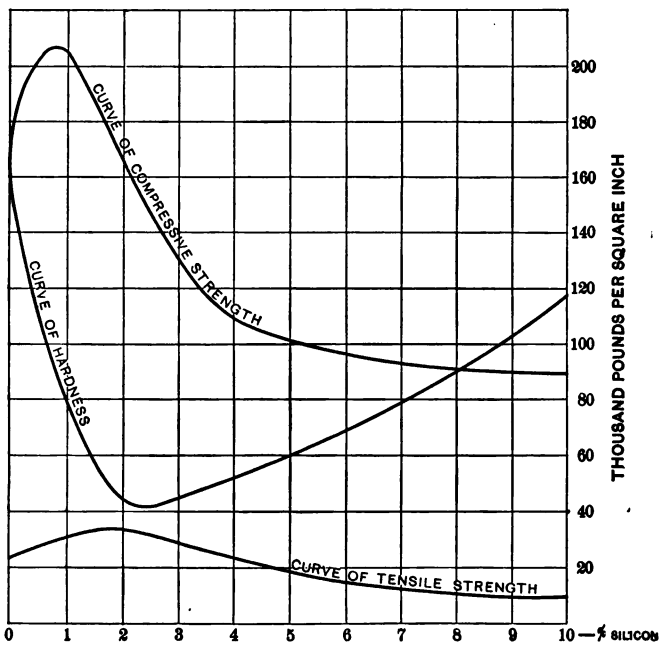

FIG. 11.

progress toward the right along the axis of X from O corresponds to conversion of combined carbon into graphitic carbon. It has been already stated that this conversion reduces compressive strength. But the curve of compressive strength rises to 0.8% silicon.

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Mr. J. W. Keep has pointed out to Mr. Turner that white iron often does not cast solid, but has blow-holes that decrease strength; and that a small amount of silicon produces sound castings.* It may therefore be that this is the first effect of silicon, and this would account for the rise of the curve. From 0.8% silicon to 4% silicon the curve of compressive strength falls rapidly, and then less rapidly till the end of the range. The curve of tensile strength rises from 0.0% silicon to 1.9% silicon and then falls gradually to the end.

The softest mixture is between 2% and 3% silicon. No data are given to show ductility, and hence no curve of resilience can be plotted. It is probable, however, that the curve of tensile resilience would follow approximately the curve of tensile strength, and that the curve of compressive resilience would follow approximately the curve of compressive strength.

Sec. 46. A varied quality of product is required from a foundry. Some castings are not subjected to any considerable stress, and the main requirement is that they shall be soft and "run sharp"; i.e., that they shall take accurately the form of the mould. The crystallizing out of the graphite causes a reduction of the shrinkage of the iron in cooling. This result might reasonably be expected, since the formation of graphite, whose specific gravity is much lower than

* Probably, as in case of steel, by increasing the capacity of iron to absorb gas.

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that of iron, must reduce the specific gravity of the whole mass, i.e., a given weight of graphitic iron would occupy a larger cubic space than if the carbon were all combined. This, in part, counteracts the effect of the natural shrinkage of the iron, and so the castings fill the mould better. Iron with a large proportion of graphitic carbon is most satisfactory for soft, sharp castings. This means iron with a large proportion of silicon. Fig. 11 shows, however, that for maximum softness silicon should not exceed 3%.

Other castings require to be as strong as possible in tension, and yet soft enough to be worked economically in the machine-shop, and also hard enough to resist wear. The maximum tensile strength coincides with almost the softest iron at 2% silicon. It is better to sacrifice something of tensile strength to gain in hardness and compressive strength, and hence about 1.5% silicon would probably be best for machine castings. If a casting were required capable of withstanding severe compressive shocks, as, for instance, an anvil-block for a steam-hammer, then, since very little machine finishing needs to be done upon it, a material should be selected with greater compressive strength, although the hardness is much greater.

If castings are required for "chilling" or for the process of malleableizing, they must be very low in silicon, as the presence of any very considerable amount of the graphitic carbon is fatal to the success

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of either process. The presence of manganese is helpful here as tending to produce white iron.

The set of curves in Fig. 11 will serve for a partial guide in the mixing of grades of iron for the production of any kind of castings. The following points must be kept in mind, however: 1st. That these results cannot be produced by means of silicon if any considerable amount of *manganese*, *sulphur*, or *phosphorus* is present. 2d. It is probable that these curves would have been modified if iron with an average total carbon had been used, say 3.5%, instead of 2%. Silicon seems to influence the physical qualities of iron (*a*) because of its effect on the distribution of the carbon; (*b*) because of its effect upon the iron itself. The former is a desirable effect, increasing strength, ductility, and softness, while the latter is an undesirable effect, resulting in decreased strength and increased hardness. In Fig. 11 evidently the influence upon carbon predominates in the early part of the series, i.e., from 0% silicon to about 2.5% silicon; while the direct influence upon the iron predominates from 2.5% silicon to the end of the series. If the total carbon had been greater, the predominance of the influence of the silicon upon the carbon might have extended further in the series.

Sec. 47. Machine castings of high strength are produced by charging about 25% of steel scrap with the pig iron. This reduces the total carbon by dilution,

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and the resulting iron has the graphite very fine and evenly distributed. The castings are soft, and easily worked, and yet have about 50% greater strength than the same iron without the addition of steel.

The effect of this treatment is quite similar to the effect of the mallifying process.* Thus the total carbon is reduced and the graphitic carbon is very fine and evenly distributed.

Sec. 48. In foundry practice it is desirable that a large amount of "scrap" be used; partly because "gates," "risers," etc., are a necessary product of every heat, and partly because a good deal of scrap is offered for sale at a low price. The effect of remelting iron is to harden it, and therefore scrap is always of harder grade than the "pig" from which it was originally cast.

The hardening effect of remelting is very clearly shown by some experiments made at the Gleiwitz foundry in Silesia, and quoted by M. Ferd. Gautier in a paper read before the Iron and Steel Institute (see Journal of 1886). The results are given in the following table:

	Original Pig Iron.	After Fourth Casting.	After Sixth Casting.
Graphitic carbon.....	2.73	2.54	2.08
Combined "	0.66	0.80	1.28
Total "	3.39	3.34	3.36
Silicon.....	2.42	1.88	1.16
Manganese.....	1.09	0.44	0.36
Sulphur.....	0.04	0.10	0.20
Phosphorus..... ...	0.31	0.30	0.30

* See Sec. 37.

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Thus the six successive meltings resulted in a decrease in the amount of silicon and manganese, and an increase in the amount of sulphur. (This latter probably absorbed from the fuel.) Graphitic carbon is decreased and combined carbon is increased; therefore the combined effect of decrease of silicon and increase of sulphur was greater than the effect of the decrease in manganese. The change necessary to convert this again into soft gray iron is the addition of silicon, provided the amount of sulphur is not too great. The reasons for the hardening effect of remelting are: (*a*) the reduction of the silicon, resulting in the redistribution of carbon; (*b*) the increase of sulphur. Of the substances which are found in combination with iron, silicon is first oxidized, manganese being next in order. Therefore, when iron is melted in the presence of an air-blast, some of the silicon is always oxidized, and usually some of the manganese. Iron is melted in the presence of anthracite coal or coke, and hence there is the possibility of absorption of sulphur. If the total carbon is sufficiently high, the softening of iron can be accomplished very satisfactorily by the addition of a proper amount of ferro-silicon, which usually contains about 10% of silicon. But if total carbon is low, pig iron high in silicon and carbon would serve better, because it would carry a larger amount of carbon per unit of silicon.

Sec. 49. "Burnt scrap" is cast iron which has

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been exposed during use to the action of oxygen at high temperatures; as, for instance, old grate-bars, salt-kettles, etc. A portion of the iron becomes iron oxide. If such iron be melted, the iron oxide gives up its oxygen to the silicon, manganese, or carbon present, in obedience to the law of affinities; and the results are silica and oxide of manganese, solids which appear as slag, and the gas carbon monoxide or carbon dioxide. The reduction of the total carbon will result in harder iron, and the reduction of the silicon will result in the appearance of all the carbon present as combined carbon. This result is so very decided that a whole heat may "run hard" because of the introduction of a comparatively small amount of "burnt scrap." If the effect of burnt scrap is due simply to the fact that the silicon has been removed by the oxygen of the iron oxide, then if it were melted together with a sufficient amount of ferro-silicon, the result would be gray, soft iron. But there might be iron oxide enough present to reduce the total carbon too much; and then the silicon could not produce gray iron, because it would not have enough carbon to work with; and in this case carbon would have to be added as well as silicon, and pig iron high in carbon and silicon would serve better than ferro-silicon. The iron oxide which is seen as rust on the surface of scrap is effective in the reduction of silicon, etc., upon melting. Its effect is of little importance, however, as it is small

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in amount relatively. It must not be concluded from this that silicon will make good iron out of all kinds of scrap. Some scrap is hopeless because of the presence of sulphur or phosphorus. It must be remembered that the addition of silicon to very gray iron can produce no good result, but rather the reverse, because the carbon is already graphitic, and the only effect of the addition of silicon is its undesirable direct effect on the iron itself.

Sec. 50. Mr. J. W. Keep of Detroit, Michigan, has made a very valuable series of experiments to determine the influence of aluminum upon cast iron.* He shows clearly that the influence of aluminum upon the distribution of carbon is similar to that of silicon, but that the effect of aluminum upon the iron itself is not an undesirable one, as in the case of silicon. It would therefore be a better material for effecting the redistribution of carbon. It is found, however, that there are some very serious practical difficulties in introducing the aluminum, either pure or as ferro-aluminum, into the cast iron.

Sec. 51. **Effect of Cooling upon Cast Iron.**—Cast iron is melted and poured into a mould. It takes the form of the mould, and cools gradually to the temperature of the surrounding air. In cooling, the iron, of course, shrinks. The shrinkage may be divided into two parts: **fluid shrinkage** and **solid shrinkage.**

* See Transactions Am. Inst. Mining Engineers, Vol. XVIII, p. 102.

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After being cast the fluid iron begins to cool, and shrinks in volume, and the fluid iron from the "runners" and "risers" runs down to supply this shrinkage, until the connection between them and the casting is frozen up. The walls of the casting are now partly solidified, but are still weak, and yield to the force of the shrinkage of the still fluid iron inside of the casting, and, if it be of large volume, depressions in the surface result. After a little the walls become strong enough to resist the force, and then, since there is no source from which to supply the shrinkage of the still fluid iron at the centre of the casting, there is no resource but for it to become "spongy." A spongy cross-section is necessarily weaker than one of solid iron, and is therefore undesirable in a stress member of a machine. The fluid shrinkage may be partly supplied by "feeding from a riser" in the way which is customary in foundries. Evidently the tendency to form spongy iron because of unsupplied fluid shrinkage will increase with the volume of the casting. After the whole casting has become solid, its dimensions are steadily reduced till it reaches the temperature of the surrounding air.

Sec. 52. Experience points to the conclusion that castings of small cross-section shrink more than those of large cross-section. To test this conclusion, Mr. Thomas D. West made an experiment which he describes in his book, "American Foundry Practice."

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He cast two bars 14 feet long, from the same iron, and as far as possible made the conditions of casting the same for both. The cross-sections were rectangular, one being $4'' \times 9''$ and the other $\frac{1}{2}'' \times 2''$. The total shrinkage for the larger bar was $\frac{7}{8}''$ and for the smaller one was $1\frac{3}{4}''$. This may possibly be explained as follows, as Mr. West suggests: A casting cools from the surface, and therefore during the cooling the surface will be the coolest part, and the heat will increase toward the centre. The external portions are held from their normal shrinkage by the resistance of the hotter internal portions, which are not yet ready to shrink as much. This goes on till the surface has reached the temperature of the surrounding air and stops shrinking; the hotter portions nearer the centre now try to shrink as they in turn cool down, but are prevented by the external part which has stopped shrinking. Whether the theory is correct or not, the fact remains that castings of small section shrink more than castings of large section. It follows that castings having thick and thin parts attached to each other will shrink unequally, and be in a state of internal stress, which renders them less able to withstand the action of external forces.

Suppose it is required to put a strengthening rib B on A, Fig. 12 (a), and that it is made of the form shown, i.e., thin relatively to A, and having parallel sides. B would shrink more than A, and shrinkage stresses

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(tension in B and compression in A) would result, which would be concentrated along the juncture of A and B, and yielding would occur under a less external force. If the form shown in (b) were used, where the rib tapers from the thickness of B to the thickness of A, the shrinkage stresses would be distributed, and the casting would be stronger.

The lessons to be learned from these facts are as follows: 1st. All parts of all cross-sections of castings for machine members should be as nearly of the same thickness as possible, to avoid concentrated shrinkage

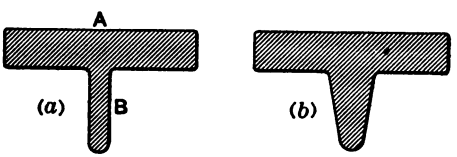

FIG. 12.

stresses, with their accompanying weakness. 2d. If it is necessary to have thick and thin parts in the same casting, change of form from one to the other should be as gradual as possible. 3d. Castings should be made as thin as is consistent with strength, stiffness, and resistance to vibration, to avoid the shrinkage stresses, and spongy metal due to the shrinkage of large masses. 4th. Since some shrinkage stresses always must exist in cast machine members, they should be taken into account in designing.

Special care should be taken in the design of wheels,

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because they are peculiarly liable to excessive shrinkage stress on account of their form. In a pulley the thin rim tends to shrink more than the heavier arms, and the rim is thereby put in tension, and the arms in compression. It is not uncommon to see a rim ruptured in this way. If the same pulley has a relatively heavy hub, the latter will remain fluid until the arms and rim have solidified; the tension on the rim will then force the arms into the yet fluid hub, which in turn shrinking, will put the arms in tension. The arms of fly-wheels tend to shrink away from the heavier rim, and are therefore in tension.

Effect of Internal Stress upon the Stress-strain Diagram.—Suppose that a casting be made of the cross-sectional form shown in Fig. 12 (*a*). The part *B* tends to shrink more than *A*, and therefore *B* is put in tension and *A* is put in compression. Where there is compressive stress and tensile force is applied, the first effect is the reduction of the compressive stress to zero. No tensile stress can be induced until the compressive stress is entirely neutralized. If a tensile force be applied to the casting (*a*), Fig. 12, it follows that no tensile stress will result in the part *A*, and therefore that all the stress will be concentrated on the part *B*. To illustrate this, suppose that a tensile force is applied to a rope, and that half of the strands are tight, and the other half are slack. Stress will result in the strands which are tight until they are strained

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so much that the others are brought into play, and then the tension is sustained by the whole cross-section, provided the strands originally tight are not broken. In the casting, the part *B* sustains the stress until the compression in *A* is neutralized, and its tensile resistance is brought into play. Because of this the unit stress (stress per unit of cross-sectional area sustaining the stress) is very great in the early part of the test, and the strain, having a proportionate value, is also much greater than it would be if the whole area of cross-section sustained the stress. The stress-strain diagram therefore takes the form shown in Fig. 13;

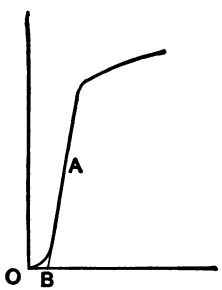

FIG. 13.

the initial part of the curve representing the concentration of stress on some fraction of the cross-sectional area. If the stress had been gradually relieved at *A*, the curve would have returned over *AB*, and *OB* would be the permanent strain or "set." If the internal stress in *B*, Fig. 12, had been sufficiently great, it might have been ruptured before the tensile resist-

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ance of A could be brought into action. In any case the piece could not sustain as great external force as if there had been no internal stress, because there would be no time during the application of force when the whole area of cross-section would offer resistance without some part having been previously weakened.

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CHAPTER IV.

WROUGHT IRON AND STEEL.

SEC. 53. **Influence of Certain Elements on Iron and Steel. Carbon.**—If carbon be added to pure iron in increasing amount up to 1.0%, the iron is changed first into mild steel and then into high-carbon steel. Accompanying this change there will be continuous increase in strength and hardness, and continuous decrease in ductility of the annealed product. After the percentage of carbon becomes great enough so that the steel will harden (say above 0.5%), the effect of the carbon to increase strength and hardness and to decrease ductility may be modified by heat treatment; i.e., the effect may be increased by hardening, and reduced to a normal value again by annealing; while intermediate values of strength, hardness, and ductility may be obtained by hardening and tempering.

Silicon.—It is probable * that the presence of silicon up to 0.8% has but little effect on the strength and ductility of steel.

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* See Manufacture and Properties of Structural Steel, by H. H. Campbell (Scientific Publishing Co.), page 257.

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Manganese.—Up to 1.0% the effect of manganese upon strength, hardness, and ductility of steel is not very great. But when the percentage rises to 1.5% the steel becomes brittle and practically useless; this effect continues until manganese equals about 7.0%; but from 7.0% to 20.0% manganese the steel has great strength, great ductility, and it is so hard that it can scarcely be cut at all with ordinary cutting-tools; in fact, it is itself used for cutting-tools and is one of the so-called "special" or "air-hardening" steels. The strength and ductility of manganese steel are both increased by quenching from a red heat in water, though the hardness is thereby but little affected. The maximum of strength and ductility is reached at about 14.0% manganese.* This manganese steel is well adapted for machine parts that require great toughness, but it can only be used where no machine finishing is required.

Sulphur.—The effect of sulphur upon steel is to make it red-short; i.e., to cause it to crack when worked at a red heat. In commercial structural steel the amount of sulphur is between the limits 0.02% and 0.10%, and the effect of such amounts upon strength and ductility is unimportant.

Phosphorus.—The effects of phosphorus upon steel may be summarized by saying that it tends to render

* See Hadfield, Journal Iron and Steel Institute, Vol. II, 1888, page 70.

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the steel unsafe when subjected to shock or any kind of vibratory load.* In specifications for structural steel phosphorus is usually required to be less than 0.06%, and in some cases less than 0.03%.

Nickel.—The effect of nickel upon steel† seems to be to raise the ultimate strength, and to raise the elastic limit in greater proportion, so that the elastic ratio (the elastic limit ÷ the ultimate strength) is increased. Nickel reduces the ductility of steel, but in less degree than the carbon which would produce the same increase in ultimate strength. Hence the nickel steel has greater ultimate resilience than carbon steel of the same ultimate strength. Its elastic resilience is also greater because of its greater elastic range. It is therefore well adapted to service requiring the resisting of shocks, as well as to service where economy of weight is of great importance.

Tungsten and Chromium.—It is found that by alloying tungsten or chromium with high-carbon steel a material is obtained which is hard enough for machine-shop cutting-tools. The hardness does not seem to depend upon the carbon present, since the usual process of heating to redness and quenching does not increase it.

There are several tungsten steels on the market, one

* See Howe, The Metallurgy of Steel, page 67.

† See Manufacture and Properties of Structural Steel, by H. H. Campbell (Scientific Publishing Co.), page 280.

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of which is the "mushet" steel. These steels are forged with difficulty at a dull-red heat, and are hard whether they are quenched or cooled slowly.

Recently a special steel has been brought out as a result of very careful investigation and experimentation by Messrs. Taylor and White at the works of the Bethlehem Iron and Steel Company. It is called Taylor-White steel and contains from 0.5% to 3.0% of chromium and from 1.0% to 6.0% of tungsten. It depends for its qualities not only upon its chemical composition, but also upon special heat treatment.

Cutting Speed of Tools.—A limit is put upon the output of a cutting-tool of hardened carbon steel because of the limit upon the cutting speed. The work of removing metal is chiefly transformed into heat, and the temperature of the work, of the chips, and of the cutting-tool rises because the heat is transferred to them. The heat is radiated away and an equilibrium is established between the rate of heat development and of heat radiation; and as a result the cutting-tool acquires a definite temperature when working conditions are established. If the cutting speed is increased, the work—and hence the heat developed—is increased proportionately, and hence the temperature of the cutting-tool, etc., must rise in order that the rate of radiation shall be sufficiently increased to dispose of the heat developed.

With given material to cut, and with given condi-

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tions of feed and depth of cut, there is therefore a correspondence between the cutting speed and the temperature of the cutting-tool; hence the output of the machine is a function of the temperature that the cutting-tool can endure safely.

If the temperature of a hardened, tempered carbon-steel tool is raised above the temperature at which the temper was drawn, the temper will be further drawn, the tool will be softened, and the cutting edge will fail.

This limits the temperature of such tools to about 450° F. Mushet and similar steels will endure a higher temperature, but fail at a much lower temperature than the Taylor-White and similar steels which will hold a cutting edge at a temperature of dull redness, about 1000° F. The introduction of these later special steels makes it possible to increase the cutting speed of tools on roughing-cuts from 100% to 300%.

Sec. 54. There may be **internal stresses** in *forged* material, similar to those resulting in *cast* material from unequal shrinkage. They are usually the result of working the material too cold. To illustrate: If a thin piece of ductile material be laid on an anvil and struck with a hammer, the piece is made thinner and longer and broader. Suppose now that the piece is thick instead of thin, and that it receives a blow as before: the influence of the blow extends only a little way into the material, and the surface is made longer

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and broader. Since its extension is resisted by the part which is uninfluenced by the blow, the material at the surface is put in compression, and the inner portion in tension. The initial part of the stress-strain diagram would be like that shown in Fig. 13. If the working be done at a red heat, the material is soft and weak, and therefore yields to the stresses introduced by the hammering or rolling, and the stresses are equalized.

Sec. 55. **Effect of Lack of Homogeneousness of Material on the Stress-strain Diagram.** — In the manufacture of wrought iron the elements of the piles of "muck-bar" or scrap are drawn out in rolling into long lines of crystals, which are separated by more or less slag or oxide of iron. Since the pile may be made up of bars or scrap of entirely different quality, the structure may lack homogeneousness. This has a tendency to modify the form of stress-strain diagram. Suppose, for example, that a test-piece of wrought iron has half of its area of cross-section of a material whose elastic limit is at E', Fig. 14, and that the other half of the cross-section is of material whose elastic limit is at E. Let a constantly increasing tensile force be applied to this test-piece. When the stress reaches the value represented by the ordinate of E, the weaker part of the material begins to yield more rapidly, and the unit stress on the stronger part is very greatly increased, its elastic limit is exceeded, it also yields, and the curve takes the form shown, running nearly

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parallel to the axis of X until the stress is again distributed over the entire surface of the cross-section; then the curve rises continuously until the maximum stress is reached.

Steel may also show this irregularity, since different parts of the forging may have different elastic limit,

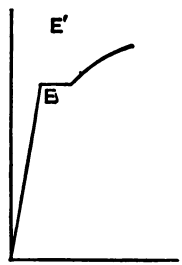

FIG. 14.

because of different heat treatment, different hot working, or superficial cold working.

Sec. 56. **Effect of Heat Treatment on the Carbon, and on the Structure of Steel.**—The carbon which has heretofore been spoken of as in combination with iron may exist in two forms. *Hardened steel* treated with cold, dilute hydrochloric acid is taken completely into solution; whereas *annealed steel* leaves a carbonaceous residue when similarly treated. The carbon in hardened steel will be called *hardening carbon*, and the carbon in annealed steel will be called *non-hardening carbon;* the temperature of the air will be called T; the temperature at which red just shows in the dark

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will be called V; the temperature of full redness will be called W; and the temperature corresponding to white heat will be called M.

Suppose a piece of annealed steel to be gradually heated from T to M. Certain changes occur in the carbon, and in the structure of the steel, which will be represented graphically. In Fig. 15, A, C, and E represent carbon change, and B, D, and F represent structure change. Temperature change is measured vertically, and change of time is measured horizontally; therefore an inclined line, like A, indicates a temperature change upward, which occupies some appreciable time, i.e., slow heating; while an inclined line, like C, indicates a gradual temperature change downward, i.e., slow cooling; and a vertical line, like E, indicates instantaneous cooling, or "quenching."

The size of circles of B, D, and F indicates, conventionally, the size of grain of the steel. In A, C, etc., light lines indicate non-hardening carbon, and heavy lines indicate hardening carbon. A shows that as the temperature of the annealed steel is gradually raised, the carbon remains non-hardening carbon till a temperature of full redness is reached, when it all turns to hardening carbon. This change of carbon at W is an *instantaneous change*. B shows that the crystalline structure remains the same as that of the annealed steel (the size of which depends on previous heat and mechanical treatment) till W is reached, when

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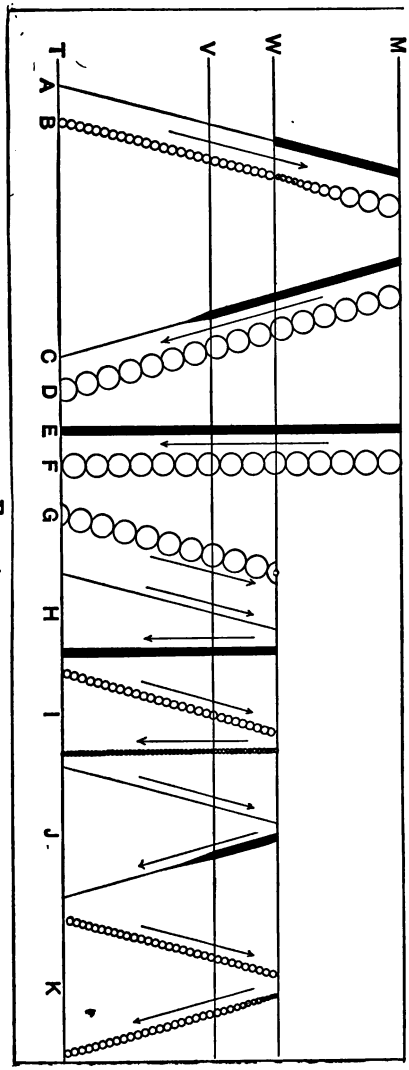

FIG. 15.

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it becomes much reduced. This change is also instantaneous, and the grain becomes as fine as is possible for the material. This is the structure which corresponds to the greatest ductility, toughness, and shock-resisting power of the material. It is therefore best for forged machine members. From *W*, with increase of temperature, the structure grows constantly coarser, and the steel more brittle and less tough, till *M* is reached.

If this steel be cooled slowly to *T*, the changes which occur are shown by *C* and *D*. The carbon does not change till a temperature just above *V* is reached, when it tends to change back to non-hardening carbon. This change occurs slowly, and the slow cooling allows it to become complete. No change of structure occurs during this slow cooling, but the coarse grain due to heating to *M* is retained.

If the cooling from *M* had been by quenching, the results would be indicated by *E* and *F*. The sudden cooling does not give time for the hardening carbon to change back to non-hardening carbon, and therefore the steel is hardened and the coarse grain of *M* is retained. The result, then, of slow cooling from *M* is to produce soft, coarse, and hence brittle steel; while the result of quenching from *M* is to produce hard, coarse, and hence brittle steel. No method of *cooling* from *M* can produce fine structure. If the steel had been raised to any temperature between *W* and *M*, the

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structure corresponding to the temperature would have been retained regardless of the method of cooling. If either the product of *CD* or of *EF* be reheated, it retains its coarse structure till *W* is reached, and then again changes instantly to fine grain, as indicated in *G*. The steel, which was made brittle and coarse by overheating, is restored by simply heating again to *W*. This restoration, however, is never perfect if the steel has been burnt, probably because of the iron oxide which has formed on the surface.

The structure changes are a function of time, and if the heating in *B* were more gradual, a still coarser structure would be attained at *M*. In *K*, if the cooling were effected more quickly, the structure would not attain the coarseness of the annealed steel.

If a piece of annealed steel be heated to *W* and quenched, it will be exceedingly hard, and the structure will be as fine as possible, because quenching, if the piece be small enough so that the cooling can be practically instantaneous, prevents change either of carbon or of structure, and both are held as they are at *W*. The material is then in the best possible condition for hardened steel. (See diagrams *H* and *I*.) If the piece of tool-steel be heated to *W* and allowed to cool slowly, the changes which take place are represented by diagrams *J* and *K*. The carbon changes back to non-hardening carbon, and the structure changes back to that of the annealed steel. The

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structure change occurs between *W* and *V*, and not below *V*. The carbon change does not begin till *V* is nearly reached, and is completed by cooling slowly from *V* to *T*.

The tendency to change hardening carbon to non-hardening carbon is probably strong at all temperatures below *V*, and in the case of hardened steel it is held from being operative by the sudden cooling, because this cooling renders the materials more resistant to the tendency to change of carbon. If, however, a piece of steel which has been hardened be slowly heated, it is found that the tendency to change becomes operative at a temperature very much below *V*. Thus, if it be heated to a temperature corresponding to the formation of straw-color oxide, there will be very perceptible softening of the steel. **If, then, steel be heated to *W*, and cooled by quenching to *V*, and then be allowed to cool slowly, the fine structure will be retained, and the hardening carbon will have had opportunity to change back to non-hardening carbon, and the material will be soft and tough.** This method was applied with great success to the toughening of car-axles by Mr. John Coffin at the Cambria Iron and Steel Works at Johnstown, Pa.

Sec. 57. If steel be melted, and quenched from the fluid state, the carbon will all be hardening carbon, and the structure will be exceedingly fine. But if it be allowed to solidify, and then be cooled by quench-

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ing, the carbon will be hardening carbon, and the structure will be coarse. If it be allowed to solidify and then to cool slowly, the carbon will be non-hardening carbon, and the structure will be coarse. These facts have been proved, and apply to the annealing of steel castings. There has been a very general impression that very slow cooling of steel castings after solidification would result in toughening and softening them. The above facts, however, lead to the conclusion that such heat treatment would result in softness and brittleness, and experience proves this conclusion. But if they be allowed to cool to *V* or below, and then be raised again to *W* and quickly cooled to *V*, and then allowed to cool slowly through the rest of the temperature range, they will be soft, fine-grained, and tough. In large castings an approximation to this heat treatment was attained by Coffin, by allowing the casting to cool to or below *V*, and then placing it in a reheating furnace where the temperature was raised to *W*. The fires were then drawn, the furnace-doors were opened, and the casting was cooled as rapidly as possible by the admission of cold air till *V* was reached, and then the furnace was closed, and the casting was allowed to come slowly to the temperature of the air.

Sec. 58. **On the Effect of Mechanical Working upon Structure.**—If steel be heated to a white heat, the coarse structure corresponding to this heat may be

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broken up and rendered fine by mechanical working, as rolling or hammering. Steel which is to be worked may therefore be heated above *W*, and still be of fine grain if the working does not cease while the temperature is yet above *W*. If the steel is worked at a temperature very much below *W*, there is a tendency to introduce stress by "cold working," as previously explained. Also steel is particularly brittle at what is usually called "blue heat" (430° to 600° F.), and if it be worked at this heat the brittleness remains on cooling. It is, however, removed by annealing. It is not possible to work large forgings so that there shall be a uniformly fine structure and no internal stress, because if forging ceases in any portion while the temperature is very much above *W*, the structure becomes coarse, and if forging continues till the iron is black, internal stress is introduced; therefore this result should be accomplished by subsequent heat treatment.

Sec. 59. **Annealing.**—By annealing is usually understood the process of heating to full redness, or above, and cooling very slowly by burying in ashes, powdered lime, or charcoal. The objects of annealing are:

1st. To relieve internal stress;

2d. To refine, i.e., to render the structure fine in grain;

3d. To change the carbon from hardening carbon to non-hardening carbon.

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Internal stresses are relieved by heating to redness. If it is required to anneal a forging which is to become a machine stress member, it should be accomplished as follows: After forging, the piece should be allowed to cool to *V* or below; its temperature should then be slowly, and uniformly, raised to *W*; it should then be quenched to *V*, and allowed to cool slowly in the air. The heating relieves any internal stresses; quenching from *W* to *V* fixes the fine structure, and confers toughness; cooling slowly from *V* affords opportunity for hardening carbon to change to non-hardening carbon, and therefore confers softness. The forging is therefore in the best condition to resist stress, and for working in the machine-shop.

Sometimes annealing is required simply to confer softness, and the piece is to be subjected to subsequent heat treatment, as, for instance, the steel which is annealed for working into cutters, which are afterwards to be hardened. In this case it is only necessary to heat the piece to *W* and bury it in lime, ashes, or charcoal until it cools. The structure will not be the finest possible, but it will be refined again by hardening.

Sec. 60. **Hardening and Tempering.**—Steel may be hardened by quenching from any temperature above *W*, but the higher the temperature the coarser the structure, and the more brittle the hardened piece. If brittleness is objectionable, as it usually is, the harden-

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ing should be accomplished by quenching from the lowest temperature at which hardness is conferred, i.e., from *W*. For most purposes the steel so hardened is still too brittle, and will not hold a thin cutting edge, and something of hardness is sacrificed to gain greater toughness, by means of the process of **tempering**, as follows: After quenching from *W*, the piece is slowly raised to a temperature at which the colored oxides begin to form on a polished surface of the piece. This softens and toughens the piece, probably by allowing some of the hardening carbon to change to non-hardening carbon. When the temperature corresponding to the required degree of softness is reached, the source of heat is removed, and the piece is allowed to cool again to the temperature of the air.

There is a strong tendency for high-carbon steel to **crack in hardening**. This is, of course, partly due to the fact that all parts cannot be cooled at the same instant or at the same rate. Thin parts will cool more quickly than thick parts; external portions will be cooled first, and internal portions afterward. This will result in unequal shrinkage and severe internal stress, just as in the case of castings. But wrought iron or low-carbon steel will not crack under the same conditions of cooling which would cause high-carbon steel to crack. The reason for this is twofold: 1st, the high-carbon steel is more brittle than the iron or low-carbon steel; and 2d, it has a greater coefficient

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of expansion. Therefore the effect of the unequal shrinkage is to produce more severe stress, and it is less able to withstand possible shock. It will be evident, therefore, that great care should be taken in the design of parts which are to be hardened. As in castings, all sections should be as nearly as possible of the same thickness, and all large masses should be avoided, as well as all sharp internal angles. As great surface as possible should be exposed to the action of the cooling medium. These precautions will insure an approximation to uniform cooling, and reduced quenching stress, and less tendency to crack.

When a thin part is necessarily attached to a thick part, it is sometimes possible to fasten another piece of metal in contact with the thin part during heating and quenching. The thin part has its thickness virtually increased thereby, so that, if the attached piece be of the right dimensions, the thin part will be cooled at the same rate as the thick part, and quenching stress is thereby avoided.

Sec. 61. **Case-hardening.** — A machine part of wrought material sometimes needs to be ductile and strong in order to resist stress, and at the same time needs to have a hard surface to resist wear. This result is accomplished by "case-hardening" wrought iron or low-carbon steel. Pieces to be case-hardened are packed in an iron box, where they are surrounded by carbon in the form of "bone-black" or animal

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charcoal; the box is sealed, placed in a furnace, and raised to a temperature of full redness; this temperature is maintained from three to twenty-four hours. The pieces are then taken from the box and dropped into water while yet red-hot. During the process the surface of the pieces has been converted into high-carbon steel by the absorption of carbon, and this steel surface has been hardened by the quenching. The core or inside portion, however, remains ductile, and is not hardened. The surfaces of case-hardened pieces must be finished by grinding. Case-hardened pieces may be treated in exactly the same way as high-carbon steel: i.e., the surface may be softened by annealing; it may be rehardened by quenching again from *W*; and it may be tempered. The inner part is unaffected by this treatment, and remains ductile.

Sec. 62. **Effect of Cold Working.**—When a piece of ductile material is strained beyond its elastic limit the character of the material is greatly changed. If, after a short interval of rest, it be tested again, its elastic limit and elastic resilience will be found to be higher, its tensile strength greater, and its ductility and ultimate resilience less. The stiffness will be but slightly changed, if at all. By cold working, i.e., by any means that gives permanent set to cold material, the elastic range is increased, the piece is made stronger and better able to resist shocks within the elastic limit, but less ductile, and less able to resist shocks exceed-

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ing the elastic limit. These changes are shown graphically in Fig. 16. The stress-strain diagram $OEABCD$ is such as would usually result from a test of a ductile material, like mild steel or wrought iron. On reaching some point, as E_1, stress is gradually relieved, and the curve descends to the X-axis at O_1. On reapplication of tensile force the curve rises along the line O_1E_1 nearly parallel to OE. The elastic limit is now at E_1, a point much higher than the original elastic limit E. The curve then continues, a little higher than it would if the stress had not been discontinued, until the maximum is reached at H.*

If the force could have been instantly reapplied at O_1, the line GHJ would probably have coincided with ABC, because the change is a function of the time of resting, after relief of stress. $OEABCD$ may be considered the stress-strain diagram of one material, and O_1E_1GHJ the stress-strain diagram of another material. It is as if a new test began at O_1. Let a represent the first diagram, and b the second. The elastic range of b, represented by O_1E_1, is greater than that of a, represented by OE. The elastic resilience of b, represented by the area $O_1E_1F_1$, is greater than that of a,

* That the maximum strength is increased has been demonstrated by Bauschinger. He first broke a long test-piece by tensile force. It was of uniform cross-section, and hence all of its parts must have been strained well past the elastic limit. He then broke one of the pieces and found increased strength. This was repeated six times, and each repetition resulted in increased strength.

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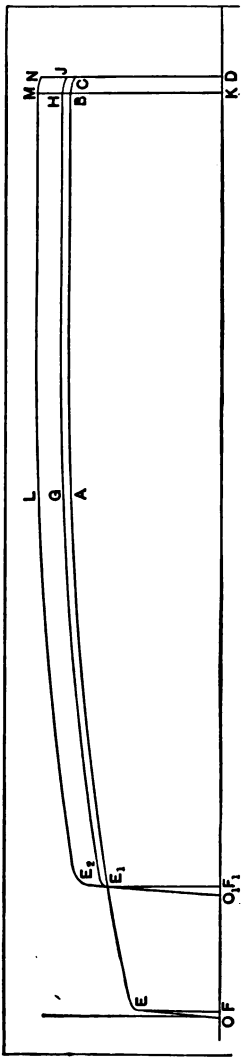

FIG. 16.

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represented by *OEF*. Experiment has proved that the points *B* and *C* are not changed in their relation to the axis of *Y* by the relief of stress; and therefore the ductility of *a*, represented by *OD*, is greater than the ductility of *b*, represented by O_1D. The ultimate resilience, proportional to the total area under the stress-strain curve, is evidently greater in *a* than in *b*. O_1E_1 is nearly parallel to *OE*, and hence rigidity is nearly the same for both.

If, instead of the *almost* immediate reapplication of force, a considerable interval of rest had been allowed, say twenty-four hours, the elastic limit and ultimate strength would have been still further raised, and the diagram would be like O_1E_2LMN. If stress were not discontinued till the maximum had been nearly reached, the strained material would resemble a very brittle material.

It may be stated as a conclusion warranted by experiment (see Trans. Am. Soc. Civil Engineers, Vol. XXIV, p. 159) that stress of any character which strains a ductile material beyond its elastic limit will render it stronger, and less ductile in resisting stress of any other character. **Annealing removes these effects almost completely**. The process of "cold rolling," by which shafting is produced, illustrates the alterations of the qualities of ductile material due to straining beyond the elastic limit. In this process iron is passed cold through highly finished rolls, under intense pres-

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sure. The rolled piece has its length increased and its cross-section reduced, and therefore, since the material takes a "set," it must be strained by the treatment past its elastic limit.

Professor Thurston made a series of tests to determine the effect of cold rolling upon iron. His experiments show that there results from the process (*a*) an increase in tensile strength of from 25% to 40%; (*b*) an elevation of the elastic limit of from 80% to 125%; (*c*) an increase of elastic resilience of from 300% to 400%; (*d*) a decrease in ductility of about 75%; and (*e*) a decrease of ultimate resilience of about 40%. If, therefore, the product of the process is required to withstand stress (and especially shock), which cannot exceed the elastic limit, it is far better than the untreated iron; but if there is a possibility of shock exceeding the elastic limit, the unrolled iron might be better.

The process of "wire-drawing," i.e., reducing the size of wire with increased length by drawing cold through dies, produces the same result as cold rolling; the wire requiring frequent annealing to restore ductility.

Sec. 63. **The Effect of Repeated Stress.**—Between the years 1859 and 1870 A. Wöhler planned and executed a series of experiments for the Prussian Government to determine the laws governing the behavior of metals under repeated stress. By means of his machines, forces of known value producing ten-

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sile, compressive, torsional, or transverse stress could be applied with indefinite repetition, until rupture occurred, or until it was considered proved that indefinite repetition of stress could not produce rupture. He formulated a law from the experimental work, which in substance is as follows: *Material may be broken by repeated application of a force which would fail to produce rupture by a single application. The breaking is a function of range of stress; and as the recurring stress increases, the range necessary to produce rupture decreases. If the stress be reversed, the range equals the sum of positive and negative stress.*

The experimental work of Wöhler has been amplified and supplemented by the very careful work of Professor Bauschinger of Munich. He draws the following conclusions from his experimental work:

a. "With repeated tensile stresses, whose lower limit was zero, and whose upper limit was near the original elastic limit, rupture did not occur with from 5 to 16 million repetitions." He cautions the designer that this will not hold for *defective* material, i.e., a factor of safety must still be used for this reason; and that the elastic limit of the material must be carefully determined, because it may have been artificially raised by cold working, in which case it does not accurately represent the material. This original elastic limit may be determined by testing a piece of the material after careful annealing.

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b. "With often repeated stresses, varying between zero and an upper stress, which is in the neighborhood of or above the original elastic limit, the latter is raised even above, often far above, the upper limit of stress, and it is raised higher as the number of repetitions of stress increases, without, however, a known limiting value, L, being exceeded."

c. "Repeated stresses, between zero and an upper limit below L, do not cause rupture; but if the upper limit is above L, rupture will occur after a limited number of repetitions."

b may be explained more fully. Suppose that a piece whose elastic limit is 28,000 pounds per square inch is subjected to repeated stress, whose limits are 0 and 29,000 pounds per square inch. Since the elastic limit is exceeded, permanent set results; i.e., the piece is "cold-worked." But the cold working raises the elastic limit, and each repetition of stress raises it more. The elastic limit passes 29,000 pounds per square inch, and the conditions are those of a material subjected to repeated stress within the elastic limit, and rupture will not result. But the elastic limit cannot be raised beyond a certain limiting value, L. If (see *c*) the limits of repeated stress are 0, and some value, T, above L, then repetition of T cannot raise the elastic limit above its own value, and the conditions are those of a material repeatedly strained beyond its elastic

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limit, and the experiments show that the piece will ultimately be broken.

From this it follows that keeping within the *original elastic limit* insures safety against rupture from repeated stress, if the stress is not reversed; and that when the stress is reversed the total range should not exceed the *original elastic range* of the material.

Sec. 64. **Factors of Safety.**—If repeated stress were the only possible cause for failure, it would only be necessary for the designer to keep the **range** of stress a little less than the original elastic limit of the material. But failure of a machine stress member may result not only from

(*a*) Repeated stress, but also from

(*b*) Flaws, or other imperfections in the material;

(*c*) Internal stresses;

(*d*) Unhomogeneous material;

(*e*) Shocks;

(*f*) Stresses which cannot be estimated.

To cover all these a factor of safety is used; i.e., the working unit stress is equal to the ultimate unit strength of the material, divided by a number which is called the factor of safety.

Materials are so various in their qualities, and the conditions to which they are subjected as machine stress members are so different, that it is impossible to give any value for a factor of safety to cover all cases.

For ductile resilient material, like mild steel used in

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building-frames, roof-trusses, bridges, etc., a low value may be used for the factor of safety, because *b*, *c*, and *d* above may be practically eliminated by proper specifications and careful inspection, and because the loads are known.

But in machines the conditions are dynamic, and it is more difficult to estimate stresses; especially when accidental increases of velocity are possible, or when lost motion, due to wear or imperfect adjustment, enable moving parts to deliver blows to other parts.

For unresilient or brittle materials, like cast iron, the factor of safety needs to be larger; not only because of less shock-resisting capacity, but because shrinkage stresses are always present, and there is, in many cases, danger of blow-holes or spongy sections. The weakening effect of these varies with the size and form of the member, and with the conditions of casting. Hence the factor of safety must be determined in each case by the judgment of the designer.

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CHAPTER V.

ALLOYS.

SEC. 65. It has been explained that iron unites with the substances carbon, manganese, silicon, sulphur, phosphorus, chromium, tungsten, aluminum, and nickel; and that the resulting mixtures have certain physical qualities due to the union. These are *alloys*, although not usually called so. It is found that nearly all of the metals used by the engineer will unite with each other in certain proportions, many of them in all proportions, and that the alloys so produced have physical qualities which differ from those of either of their constituents.

The subject of the constitution of alloys is being investigated very exhaustively with the aid of microscopic examination. A discussion of this very interesting subject is beyond the scope of this work, and the student is referred to Vols. I and II of "The Metallographist," edited by Albert Sauveur, published by the Boston Testing Laboratories, 446 Tremont St., Boston, Mass.

Sec. 66. The alloys of greatest importance to the engineer are the copper alloys, i.e., the combinations

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of copper with some one or more other metals, in varying proportions.

Alloys of *copper* and *tin* are usually called **Bronze.**

Alloys of *copper* and *zinc* are usually called **Brass.**

Alloys of *copper*, *tin*, and *zinc* have been named by Dr. Thurston **Kalchoids.**

Bronze.—If successively increasing amounts of tin be added to pure copper, it is found that certain changes occur in color, strength, and ductility. The changes in strength and ductility may be represented graphically. The curves in Fig. 17 are plotted from the very complete experiments of Dr. Thurston (see "Text-book of the Materials of Construction," page 451). From these curves it appears that as the amount of tin is increased, the strength increases until tin 18%, copper 82% is reached; from this point to tin 30%, copper 70%, the strength falls off very rapidly; and the alloy remains weak through the rest of the range. The ductility rises from tin 0, copper 100, to tin 4, copper 96, and then falls to zero at tin 22, copper 78. The ductility rises again near the tin end of the range to a very high value. The curves show that the only part of the range where strength and ductility are both high, and where resilience is therefore also high, is between tin 10, copper 90, and tin 0, copper 100. In practice "gun-bronze" is practically the only bronze used for machine parts. Its composition varies but little from tin 10, copper 90.

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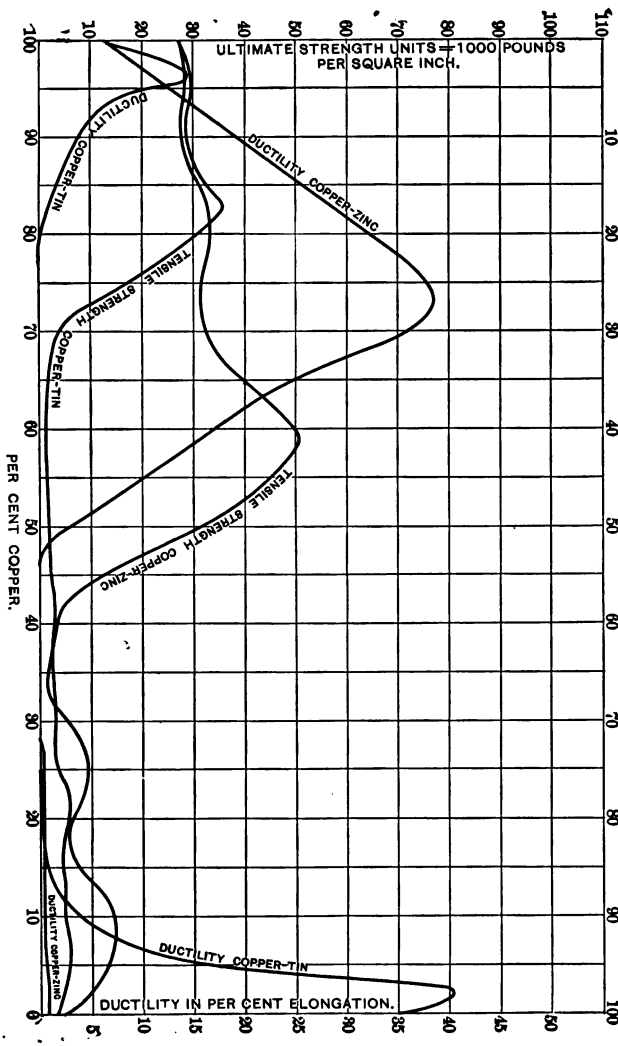

FIG. 17.

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The increasing strength resulting from increased proportion of tin is accompanied by increasing hardness and decreased coefficient of friction; i.e., it has become a better material for journal-bearings. The alloy from copper 70 to copper 10 is evidently a very brittle material. But from copper 10 to copper 0 the high ductility and low strength show a resilient, weak material. The coefficient of friction is, however, less even than that of the alloys at the other end of the range, and it is therefore a good material for journal-bearings and slides; but it is so weak that it has to be enclosed in shells of stronger material; i.e., it is used as a lining for brass or cast-iron journal-boxes. A small amount of antimony added to this gives the alloy known as Babbitt metal. Tin 33, copper 67, gives an alloy which, while it is evidently exceedingly brittle, yet it is susceptible of a very high polish, and is used for the metallic mirrors in certain optical instruments. It is called "speculum-metal." Tin 23, copper 77 is a strong alloy, lacking in ductility, which, because of its sonorousness, is used for bells. It is called "bell-metal."

In proceeding from the copper to the tin end of the range the color changes, first, from the color of pure copper to a yellow at copper 80, turning to gray at copper 70, and changing gradually to tin color during progress toward copper 0.

Sec. 67. **Brass.**—Fig. 17 also shows curves of

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strength and ductility of the brasses or copper-zinc alloys. These are also drawn from the results of Dr. Thurston's experiments (see "Text-book of the Materials of Construction," page 461). Inspection of these curves shows that the copper-zinc mixture offers a much wider range of alloys useful to the engineer than the copper-tin mixture; the range, both of high strength and high ductility, being much greater in the former. The addition of zinc to copper has an effect similar to that of the addition of tin to copper. The maximum effect is greater in the case of zinc, but it requires a greater percentage of the zinc to produce it. The color changes are similar to those in the copper-tin mixture. There is no return of ductility at the zinc end of the range, and hence the white alloys of copper and zinc are seldom used. The curves may be used to indicate proportions in mixing bronzes or brasses for any special duty requiring strength, ductility, and resilience.

Sec. 68. **Kalchoids.**—Dr. Thurston made a very full and careful series of experiments on the kalchoids, or ternary alloys of copper, tin, and zinc. He represented the whole field of possible combinations of the three metals by an equilateral triangular area. Many points at equal distances from each other were located in this area, and each represented an alloy with certain proportions of the three constituents. Alloys were made corresponding to each point, and tested. At

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each point was erected a piece of wire whose height represented the strength of the alloy represented by the point. Plastic material was then filled in between the wires, and its surface was moulded so that the points of the wire just showed through. This surface represented topographically the varying strength of all possible mixtures of copper, tin, and zinc, and the alloy of maximum strength was thereby located. (See Thurston's "Text-book of the Materials of Construction," page 466.)

Sec. 69. Two other alloys of copper require attention: *phosphor bronze and manganese bronze.*

Phosphor Bronze.—When any alloy containing a high percentage of copper is melted in contact with the air, there is a strong tendency to form copper oxide, the affinity of copper for oxygen being exceedingly strong. If the alloy cools mixed with copper oxide, it is weak and brittle, just as iron containing iron oxide is weak and brittle. Copper alloys are usually melted with charcoal upon the surface to prevent oxidation, but the prevention is not complete. If phosphorus be added to the alloy just before pouring, the copper oxide is reduced and phosphoric acid is formed, i.e., the alloy is purified by the fluxing action of the phosphorus. This increases both the strength and ductility of the alloy. If an excess of phosphorus be added, part of it may combine with the alloy and increase its strength and ductility; but it is probable

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that the chief value of its presence is to prevent the formation of oxide of copper during remelting.

Manganese Bronze is made either by fusing together (*a*) copper and black oxide of manganese, or (*b*) copper or bronze and ferro-manganese. In the first case the product is an alloy of copper and manganese, and in the second an alloy of copper, manganese, and iron, or copper, tin, manganese, and iron. Some of the manganese is effective in removing, or preventing the formation of, oxide of copper, while the remainder combines with the copper or bronze to give it very greatly increased strength, ductility, and toughness. A manganese bronze, copper 83.45%, manganese 13.48%, iron 1.24%, has a strength and ductility equal to that of open-hearth steel with 0.2% carbon. It is much used for marine propeller-wheels because it does not corrode easily.

All of the useful copper alloys are more or less forgeable. "Muntz metal," copper 60, zinc 40, is rolled at a red heat into plates for sheathing ships, and into forms for bolts and other fastenings. It is stronger, cheaper, and more durable than pure copper. The effect of cold working upon the copper alloys is similar to that upon iron and steel; viz., the strength and hardness are increased and the ductility is decreased, and hence the material is more brittle. This will be clear on comparing hard-drawn brass wire with the same wire after annealing.

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CHAPTER VI.

SELECTION OF MATERIAL.

SEC. 70. The more important materials used in machine construction may be brought together in a table as follows:

1. High-carbon Steel.
2. Mild Steel, produced by the Bessemer or open-hearth process.
3. Wrought Iron.
4. Cast Iron.
5. Malleableized Cast Iron, or Malleable Iron.
6. Steel Castings.
7. Brass or Bronze.
8. White Metal. This name includes all of the white alloys used for lining journal-boxes, etc.

The qualities upon which selection chiefly depends are indicated in the table on page 123

Sec. 71. The fitness of materials for wearing surfaces also needs consideration.

The surfaces of machine parts that move over each other under pressure are normally separated by a film of lubricating material. But under exceptional conditions the metallic surfaces themselves may come into

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contact; when this occurs the danger of roughening or destroying the surfaces depends somewhat upon the excellence of the surface and kind of material.

Material.	Tensile Strength.	Compressive Strength.	Resilience or Shock Resistance.	Shaped for Use by
1	very high	very high	medium	forging
2	high	high	high	forging
3	medium	medium	high	forging
4	low	very high	low	casting
5	medium	——	high	casting
6	high	high	high	casting
7	low	——	medium	casting or forging
8	very low	——	——	casting

A material may be well adapted for wearing surfaces because of (*a*) hardness, (*b*) slipperiness, (*c*) homogeneousness, or (*d*) because it is partly composed of lubricating material.

Thus, (*a*) hardened tool-steel is difficult to roughen because of its hardness; (*b*) white metal, though soft, is difficult to roughen, because the roughening agent slides over the slippery surface; (*c*) mild steel would have less tendency to roughen an engaging surface than wrought iron, because the former has a homogeneous surface, while the latter carries streaks of gritty cinder; (*d*) cast iron tends to wear smooth rather than rough, because it contains graphitic carbon, a lubricating material.

The ideal for rotating surfaces would be a hardened, accurately ground, crucible-steel journal, with its

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bearing lined with white metal. But here the question of cost enters, for the cost of the journal specified includes high first cost for the crucible steel, the cost for hardening, and a cost incident upon the loss of expensive parts through cracking in the process of hardening. In addition to this, an expensive plant is required for the hardening of large journals.

In standard practice mild-steel journals are used with bearings lined with white metal; but there are often conditions that lead to the use of other materials.

Sliding surfaces in machines are often formed upon cast-iron members, and the engaging surface is also of cast iron. The frictional loss may be reduced by giving one surface a white-metal covering.

Sec. 72. To illustrate the selection of materials for machine parts, a few typical examples will be discussed.

The **cylinder of a steam-engine,** with its ports and its connected steam-chest, is of such complicated form that it would be almost impossible to shape it by forging; or if the forging were possible, it would be too expensive. The possible materials which may be used for such a cylinder are, therefore, only those which are shaped by casting. Brass and bronze would have no advantage over cast iron, and would cost about ten times as much. They are, therefore, out of the question. Steel casting might be used, but the first cost of the material would be somewhat greater, and the cost

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of working in the machine-shop would be very much greater. Additional strength and resilience would be gained, but this is unnecessary, as cylinders, even for very high pressures, can be made of cast iron, amply strong and resilient, and yet not objectionably thick. Moreover, cast iron is one of the very best possible materials for the wearing surfaces of the cylinder and valve-seat. Cylinders subjected to excessively high pressure, as 300 to 700 pounds per square inch, should perhaps be made of steel castings; as, for instance, the cylinders of pumps for pipe-lines, or for supplying hydraulic machinery.

The **piston-rod of a steam-engine** is of mild steel. The entire force of the steam acting on the piston must be transmitted to the cross-head through the piston-rod; also, since the effective area of the piston on the crank side equals the total area of the piston less the area of the rod, and since the effective area needs to be as large as possible, the rod should be as small as possible. There is always the liability to shocks, and therefore, since the rod must be small and at the same time strong, and must also be capable of resisting shocks, a material is required of high unit strength and of high resilience. Soft steel is the material which combines these qualities.

A **steam-engine cross-head pin** is always made much larger than is necessary to safely resist shearing, or springing by flexure, to insure the maintenance of

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lubrication; cast iron might serve, then, as far as strength and stiffness are concerned, and in fact is sometimes used. But there is another important consideration: because of the vibratory motion of the connecting-rod on the pin, there is a tendency to wear the pin oval, and when the boxes are "keyed up," they will bind when the rod is in its position of greatest angularity, if it is properly adjusted when the rod is on the centre line of the engine. Because of this it is desirable to reduce the wear to a minimum, and this points to the selection of a hard material. Hardened tool-steel might be used, but it is more expensive than soft steel or wrought iron, and there is the danger of hidden cracks, resulting from the hardening, which may cause accident. If soft steel be case-hardened, it will combine a hard surface to resist wear, with a soft resilient core, free from the danger of cracks. Wrought iron case-hardened might be used, but wrought iron, because of the method of manufacture, has streaks of cinder in its surface, and lacks the homogeneity of the steel, and is therefore harder to make, and to keep truly cylindrical. It therefore should not be used where perfection of bearing and accuracy of movement are essential.

The **connecting-rod of a steam-engine** is subjected to the alternate tension and compression resulting from the pressure on the piston, and also to a flexure stress due to its vibratory motion. These stresses are very

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severe, and there is also liability to shock. The material of the rod should be strong and resilient, and soft steel would naturally be selected, since it is a forgeable material. But there is another important consideration. The rod is to be finished, and wrought iron is much more cheaply worked in the machine-shop than soft steel, and the expense of forging is also much less. The lack of homogeneity is of no importance, as no part of the rod is a bearing-surface. Many connecting-rods are made of steel casting, and finished by painting. This makes a cheaper rod, but there is always the danger of hidden defects, like cracks, due to the excessive shrinkage, or "blow-holes," which may weaken the rod enough to cause accident.

Sec. 73. The **cross-head of a steam-engine** is composed of two parts: (*a*) that which serves to transmit the pressure from the piston-rod to the cross-head pin, and (*b*) that which engages with the guide to produce rectilinear motion. The stresses on (*a*) are severe, and there is liability to severe shock; hence it must be of strong resilient material; the stresses on (*b*), however, are less, but it must be of material which will run well with the guide, which is usually of cast iron, being a part of the engine-bed. The cross-head may be made of materials as follows: (*a*) may be made of forged wrought iron or soft steel, and (*b*) may be of cast iron bolted to (*a*), or the whole cross-head may be made of cast iron, the part (*a*) being made enough

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larger than before to be sufficiently strong; or the cross-head may be made a casting of steel and a "shoe" or "gib" of cast iron or brass may be added to provide a proper surface to run in contact with the guide.

The **crank-pin of a steam-engine** is subjected to the same stress as the cross-head pin, and the velocity of rubbing surface is very much greater, hence the tendency to wear is greater. But the tendency to wear "out of round" is less and therefore there is less interference with the correct adjustment of the boxes; hence there is less reason for keeping the wear a minimum; a good journal surface is necessary, and soft steel is used without case-hardening.

The **main shaft of a steam-engine** needs to be strong and rigid to resist a combination of severe stresses, i.e., the torsional and transverse stress from the connecting-rod, and the transverse stress due to the weight of the fly-wheel, and the belt tension. It must also afford a good journal surface, and for these reasons it is made of soft steel.

The function of the **fly-wheel** of a steam-engine is to adapt a varying effort to a constant resistance, and it does this by absorbing and giving out energy periodically by virtue of its inertia, which is proportional to its weight; it therefore needs, above all things, to be heavy; it also needs to be able to resist the bursting tendency of the centrifugal force due to

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its rotation. The most suitable material is therefore that which gives the greatest weight in the required form, with the required strength, for the least money; and cast iron best fulfils these requirements.

An engine bed or frame, when it is in one piece, is of cast iron, and the reasons are obvious: its form is complex, and could only be produced by casting; weight is not objectionable, but rather an advantage, since it absorbs vibrations; cast iron is amply strong, and affords good wearing surfaces for the cross-head guides. Wrought iron is used for engine-beds where vibrations are less important, as in the locomotive, and where lightness and compactness are very desirable, as in some marine engines. The beds of some large roll-train and blowing engines are built up of wrought and cast iron.

The **journal-bearings,** or boxes for the cross-head pin, the crank-pin, and the journals of the main shaft are usually made now of cast iron or brass, with a Babbitt-metal lining, because, first, good Babbitt metal (tin 80, copper 10, antimony 10) is found to be a better bearing metal than brass, i.e., it runs with less tendency to heat; and second, in the case of the cutting out of the surface, the Babbitt-lined box is far more quickly and cheaply renewed than the solid brass box.

The **eccentric** and its **strap** are almost invariably made of cast iron, because they are forms which are

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forged with difficulty, and the cast iron affords ample strength and excellent wearing surfaces. The **eccentric-rod,** on the other hand, would be cumbersome and ugly in appearance if it were made of cast iron and given sufficient strength. It is a form which may be easily either forged or cast, and is made of forged wrought iron or steel, or of cast steel, or of malleableized cast iron. **Rocker-arms** also, when they are used, require to be of a resilient material, and when of simple form may be forged of wrought iron or steel, and when of more complex form may be of malleableized cast iron, or steel casting. The **valve** is usually of somewhat complex form, and needs to wear well with the cast-iron valve-seat, and is almost invariably of cast iron.

Sec. 74. Considerations similar to those above apply to the selection of proper material for the parts of **machine tools.** Thus, in the case of a lathe, the bed, legs, head, and tail-stock, cone, gears, etc., are of cast iron, because they are all forms which are most cheaply and satisfactorily produced by casting, and the cast iron affords the required strength and stiffness, and satisfactory wearing surface, where they are required. Such parts as lead-screws, feed-rods, and other parts which are subjected to some considerable stress, and have great length relatively to their lateral dimensions, are made necessarily of wrought iron or steel. Many of these parts may be finished in the machine-shop

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directly from merchant-bar stock, thus saving expense for forging.

The material for the parts of planing-, milling-, and drilling-machines are determined from exactly similar considerations.

Spindles, however, require special attention. In lathes, milling- and grinding-machines the accuracy of the work produced depends largely upon the accuracy of the spindle.

The vital point is therefore to maintain this accuracy, i.e., to prevent wear as far as possible. It would seem then that hardened tool-steel would be the best material. But since only a very small amount of stock can be removed by the grinding-machine after the piece is hardened, the spindle must be roughed out very nearly to size before it is hardened; this involves a very considerable expense, and there is danger that it may crack in hardening, or spring so as not to hold up to finish, in which case the loss is great, and it is found that the risk cannot be taken. The next best thing is to specify machinery steel high in carbon (say 0.4%), and to use this harder material for the spindle without hardening. In milling-machines and in some lathes the main spindle-box is solid, of tool-steel, hardened and ground (the risk of loss being less in this case), and the spindle as before is of 0.4% carbon machinery-steel. The wear is thus greatly reduced, and the possibility of wear after long use is provided

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against by making the bearing taper, and providing end adjustment. The spindles of very large lathes are made of cast iron, because forged material would be too expensive. The wear is reduced by making the journals very large.

Sec. 75. In the steam or hydraulic **riveter** the main frame which supports the cylinder, and carries the guide for the moving die, may be of any reasonable size, and therefore can be made strong enough to resist even the very great forces applied to it, if the material used is cast iron. But the "stake," the member which carries the stationary die, must resist exactly the same forces as the main frame, and must also be small enough so that small boiler-shells, and even flues, can be lowered over it to be riveted. The "stake" is therefore of forged wrought iron or steel, or else a steel casting.

Sec. 76. Suppose that in a machine there is need of a **gear** and **pinion** whose velocity ratio is 8 to 1, and that the force transmitted is large. A tooth of the pinion comes into action eight times as often as a tooth of the gear, and therefore would wear out in one eighth of the time if both were of the same material; then, too, the form of the pinion-tooth in most systems of gearing is such that it is much weaker than the gear-tooth. The material for the pinion needs, therefore, not only to be stronger, but also better able to resist wear. The gear is made of cast iron; if the teeth are

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cut, the pinion may be made of forged steel; if the teeth are cast and used without "tooling," the pinion may be made a steel casting.

Sec. 77. **Material for Springs.**—Springs are useful as machine parts because of their capacity for yielding without taking permanent set. The yielding, therefore, must occur with stresses that do not exceed the elastic limit. Clearly, then, the material with large elastic range, i.e., with high elastic limit, is the best material for spring machine-members.

Crucible-steel has the highest normal elastic limit, and this limit is raised by hardening and tempering. This is the most commonly used material. Untreated mild steel may also be used, but with given stress the spring must have greater weight than if higher carbon steel were used. The steel may have its normal elastic limit artificially raised by cold working (cold rolling or wire-drawing), and this improves it as a spring material. Brass, bronze, and other alloys are used for springs, but usually in the form of hard-drawn wire with an artificial elastic limit.

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